SEISMIC AND ENERGY INTEGRATED RETROFITTING OF EXISTING BUILDINGS: TWO CASE STUDIES IN ITALY

V. Pertile(1), A. Stella(2), L. De Stefani(3), R. Scotta(4)

(1) *Ph.D. Fellow, University of Padova, valentina.pertile@dicea.unipd.it*
(2) *Ph.D. Fellow, IUAV University of Venice, astella@iuav.it*
(3) *Research Fellow, University of Padova, lorenzo.destefani@dicea.unipd.it*
(4) *Professor, University of Padova, roberto.scotta@dicea.unipd.it*

Abstract

In most of the developed countries, a large part of the building stock is affected by high energy consumption. The lack of thermal insulation of the building envelope leads to high heating and cooling costs. Furthermore, in seismic prone regions, the same buildings present high earthquake vulnerability because they were designed only for vertical loads, according to old regulations. In the last decades, the problem of climate change and the reduction of emissions in the atmosphere have become increasingly important. Environmental and economic aspects make the demolition and reconstruction of all the inefficient buildings not feasible. It is then necessary to find an integrated solution that improves both the energy efficiency and the structural resilience to extend the service life of these constructions and to reduce their environmental impact. The development and application to real buildings of an original technology for the integrated retrofit of existing buildings are presented. The aim is to improve both seismic resilience and thermal insulation. The technology consists in the realization of a lightly reinforced concrete skin applied only to the outer surface of the existing building. The concrete skin is cast on-site into insulated formworks and is anchored to the existing structure by metal connectors. The installation method, the typical geometry, and details of the system are discussed. Two case studies demonstrate the feasibility of the integrated retrofit with the technology studied. The seismic vulnerability of the two buildings before and after the retrofit intervention is assessed. The chosen buildings have a different structural system (masonry walls and RC frame) to show the effectiveness of the intervention on different types of constructions.

Keywords: Integrated retrofitting; Existing buildings; Case study; Building envelope; Seismic risk

1. Introduction

Almost 50% of the Earth's surface is subjected to seismic risk as Global Seismic Hazard Map [1] shows. The higher seismic hazard is located on the west coast of the American continent, on the southern part of the European continent, on the northern part of the Middle East region, on the territory between China and India, on the islands of the South East Asia (Philippines, Indonesia, Papua New Guinea), and the islands of East Asia (Japan). The regions mentioned above have a high level of anthropization, so the assessment of the seismic vulnerability of the building stock is fundamental to determine the risk for human lives and to plan the structural retrofitting needed to prevent life loss.

Seismicity in Europe is not evenly distributed; the northern nations have a low seismic risk, while the southern nations like Italy, Greece, and the Balkan region have a high seismic risk. For this reason, the evolution of seismic design codes was different in each European country [2]. Most of the European building stock was built before 1960 when only a few countries had design codes with limited seismic provisions; this means that there are a considerable number of existing buildings with different functions (dwellings, schools, offices) that have insufficient earthquake resistance. Moreover, a number of these buildings reached their nominal structural service life (50 years for residential buildings, according to Eurocodes). Many authors studied the theme of obsolescence of buildings. Thomsen and Van der Flier [3] analyzed the factors that influence the obsolescence, giving a conceptual model; Bradley and Kohler [4] introduced the definition of economic service life alongside with the service life definition given by ISO standard, to decide if the demolition is necessary or if retrofitting can extend the life of the structure. In the life cycle assessment of a building, the demolition and reconstruction process is often more expensive than the retrofitting intervention; moreover, it produces more waste and pollution that affect the global climate change.

Low energy efficiency also characterizes the vulnerable building stock mentioned above. Due to the low thermal insulation of the building envelope, the heating/cooling system is one of the principal causes of energy consumption and CO_2 production. Many international institutions and governments developed design protocols to reduce the impact of the buildings on climate change. Moreover, many countries have earmarked consistent funds to promote the renovation of buildings [5].

In this scenario, it is essential to develop integrated retrofitting technology that allows achieving better seismic performance and reduction of energy consumption at the same time. Different solutions have been proposed: from the exoskeleton [6] to the “structural skin” [7], all focused on the application outside the building. This critical aspect allows not to interrupt the activities inside the building during the renovation process, minimizing the economic loss due to interference between them and the construction site.

2. Description of the retrofitting technology

This work presents the application of a retrofitting technology [7] developed to improve the energy and structural performances of existing buildings. The system is composed of a thin reinforced concrete membrane cast on-site within a permanent formwork consisting of two layers of insulating material. The formwork is produced off-site, and its conformation allows to guarantee uniform thickness for the reinforced concrete layer and the correct placement of the rebars. Given the reduced thickness of the structural layer, rebars consist of a single layer of horizontal and vertical bars in a barycentric position. The diameter and the position of the rebars can be modulated according to the seismic actions expected for each specific building.

The system is designed to resist horizontal actions, whereas the existing structure withstands vertical loads. Due to the reduced thickness of the membrane, it can be subjected to buckling phenomena. It is possible to create horizontal and vertical ribs by interrupting the internal layer of the insulating formwork to avoid the buckling phenomena (Fig.1). The ribs have a higher thickness than the slab and have longitudinal bars and stirrups like traditional beams. The ribs increase out-of-plane stiffness of the structural layer, and the failure occurs due to the ultimate resistance of the materials, instead of buckling.

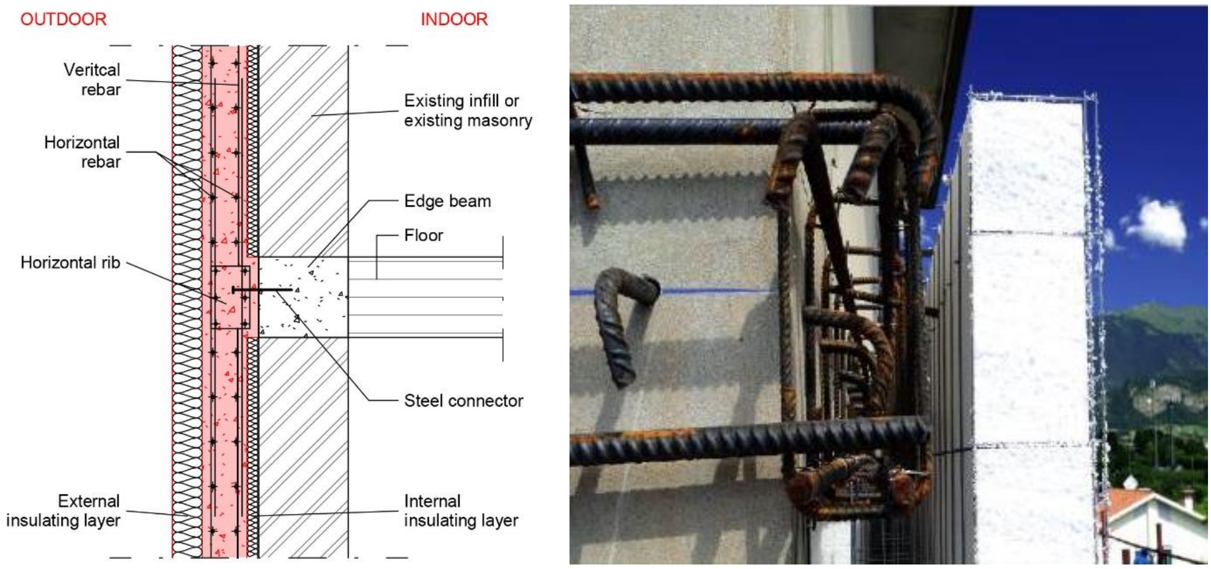

Fig.1 – a) Vertical section b) Reinforcement of the concrete rib

The retrofitting system is connected to the existing structure at each story, using steel connectors embedded in the horizontal ribs. The number and diameter of the connectors are chosen according to the expected horizontal force. If the existing foundation system is sufficient to resist seismic load, the new structural system can be directly connected using dowels. Otherwise, a new foundation system must be designed.

The insulated formwork material has low transmittance value; this contributes to improving the energy performance with better thermal insulation of the building envelope. The energy consumption linked to the heating and cooling system is then reduced. Insulated formwork can be made of different materials to obtain desired characteristics of thermal-acoustic insulation, and reaction to fire.

3. Cyclic test on full-scale masonry building specimen

An experimental campaign on full-scale specimens was performed to assess the mechanical behavior and the ultimate resistance of the retrofitting technology presented herein [7]. Quasi-static cyclic tests were performed on different specimens to define the seismic response of the technology applied. Two types of specimens were tested. Type A specimens were made by a supporting structure (masonry wall or reinforced concrete frame) and the reinforcement system applied on both sides. Type B specimen was a one-story masonry building with the retrofitting system applied only outside. The cross-section of every specimen was symmetric to prevent warping when the in-plane cyclic load is applied.

Test results of the Type A specimens confirm the ultimate resistance calculated analytically. All the specimens have shown a brittle failure mode; therefore, the design of the thin reinforced concrete layer of the retrofit system should consider only the elastic field. In this work, the results of the test on Type B specimen are presented.

3.1 Set-up description

A reaction structure was built to perform the experimental campaign. It consists of two reaction walls built on a foundation slab having the following dimensions: 1m thickness, 3.5m width, and 12.5m length. The high thickness of the slab minimizes the deformation during tests and gives a fixed plane for the measurement instruments. The two reaction walls have the same dimensions: 1.5m length, 3.5m height, and 0.4m thickness. Every reaction wall can resist a horizontal load higher than 1000kN. The described set-up allows the construction up to four specimens at the same time, before testing.

The horizontal cyclic load was applied to the specimen with a double-effect hydraulic actuator positioned between the specimen and the reaction walls and connected to a steel bar located between the walls and the floor (Fig.2). The bar was made of S355 structural steel and had a 45mm diameter. The applied load was measured continuously with a load cell. Linear potentiometric displacement transducers measured horizontal and diagonal displacements. Horizontal displacements were measured on four points at the top and one point at the bottom of the specimen.

During the test, a displacement controlled cyclic load history was applied. The horizontal top displacement was the reference measurement, and the maximum drift considered was equal to 1%. In the incremental load history, every target displacement has been repeated two times. In the first part of the test, velocity was equal to 0.001mm/s, and then it increased up to 0.1mm/s at the end of the test.

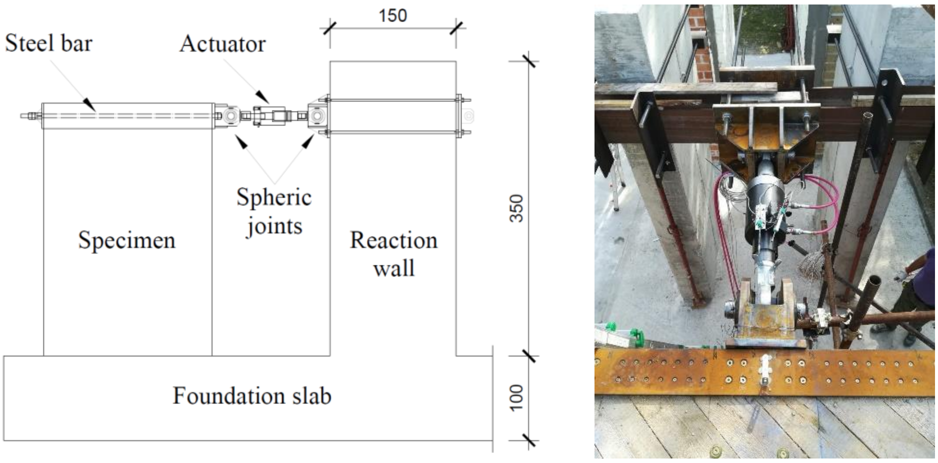

Fig.2 – a) Setup scheme b) Loading system picture

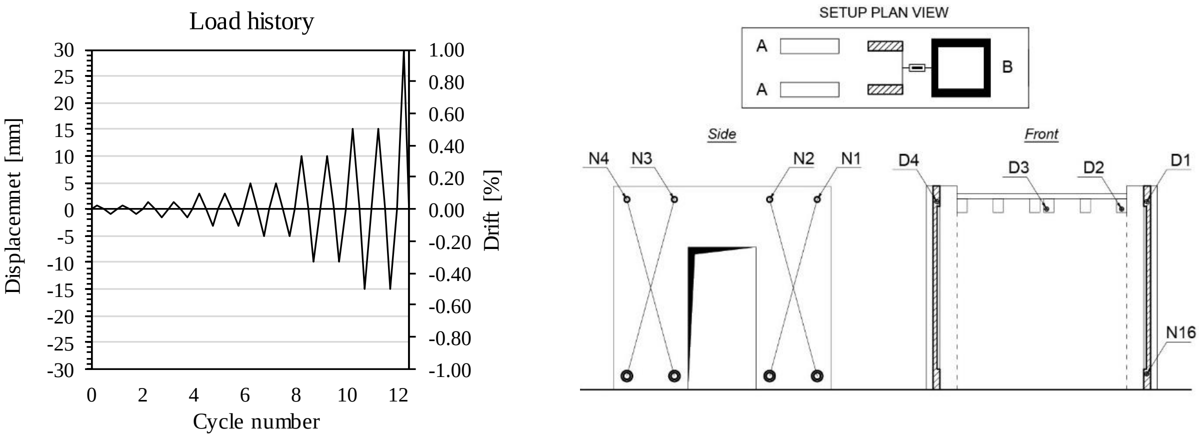

Fig.3 – a) Load history b) Sensors positioning

3.2 Specimen description

The specimen presented in this work is a one-story real scale masonry building. The perimeter walls were 3m high, consisted of multi-hole clay brick, and the plan dimension was 3.2mx3m. The walls parallel to the loading direction had a door opening (1m long and 2.1m high), the perpendicular walls had no openings. In the direction parallel to the load application, the walls were strengthened with the technology described in Section 2. The final wall section, from the inner to the outer side, was composed of 250mm brick masonry, 40mm EPS insulating formwork, 60mm RC structural layer, 100mm EPS insulating formwork. The total thickness of the retrofitted walls was 450mm. At the top and the bottom of the retrofitted walls, the interruption of the inner insulating layer formed two horizontal ribs with a cross-section of 100x300mm. The ribs were reinforced with four Ø6mm longitudinal rebars and with Ø8mm stirrups, with a spacing of 200mm. The concrete layer was reinforced with Ø6mm vertical and horizontal rebars, with a spacing of 300x300mm. Additional Ø10mm rebars were placed around the door opening, on top and bottom of the RC spandrel, and at the ends of the walls. The connection of the strengthening concrete layer to the foundation slab was made using Ø16mm dowel rebars with a spacing of 150mm. The concrete used for the structural layer was class C25/30, and the rebars were class B450C according to Italian regulation.

The roof consisted of a wooden floor with timber beams parallel to the loading direction, one layer of planks perpendicular to the beams, and a second stiffening layer of timber boards at 45°. The floor is connected to the walls by means of steel plates of class S355 and section 140x14mm or 160x14mm. The steel plates perpendicular to the loading direction are connected directly to the timber beams with 12x160mm self-tapping partially threaded screws through the two-layered timber boards. The steel plates parallel to the loading direction are connected with steel U-shaped hooks Ø14mm to the timber floor and bonded into the horizontal top ribs of the structural layer of the retrofitting technology applied. Due to the structure of the floor, it is possible to assume the rigid diaphragm hypothesis [8].

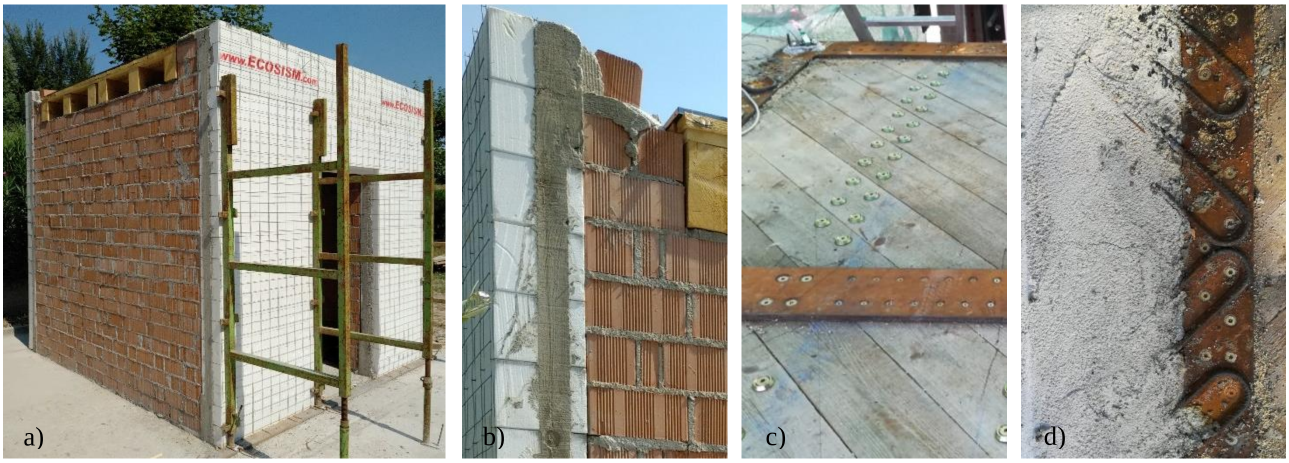

Fig.4 – a) One-story building specimen b) Detail of the retrofitting technology applied
c) Timber floor d) Detail of the connection between the timber floor and the concrete layer

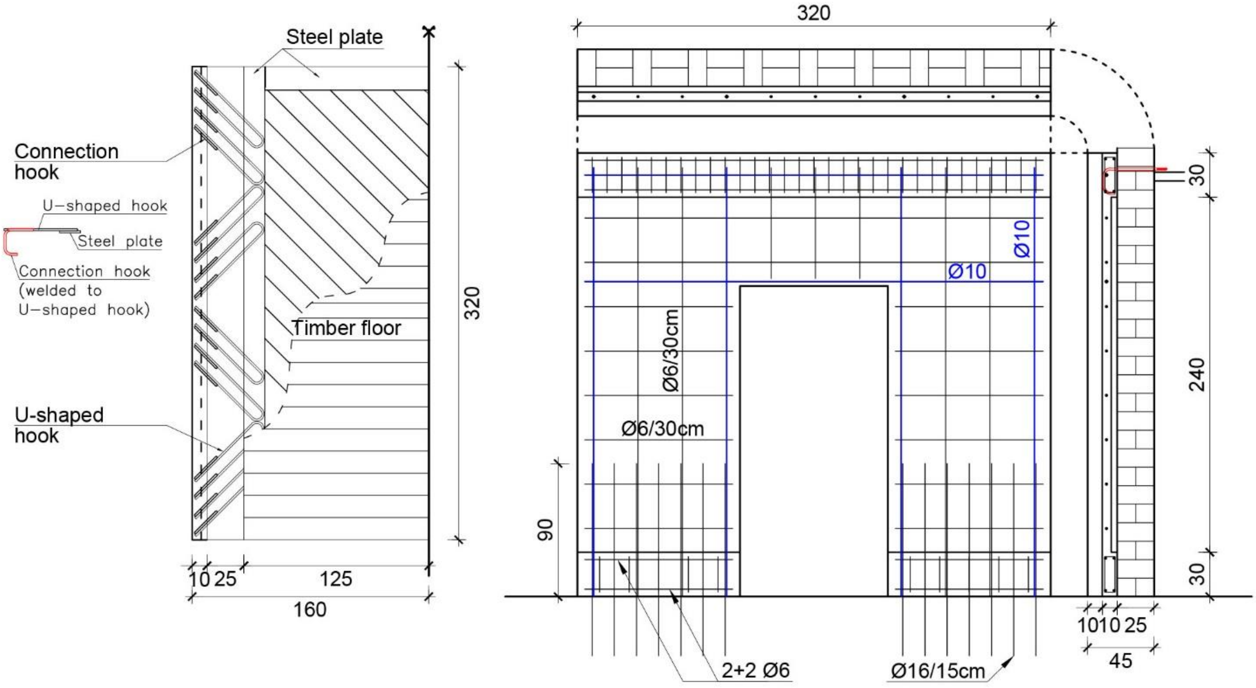

Fig.5 – Details of reinforcement and connection with the timber floor

3.3 Full-scale test results

The specimen showed a maximum resistance of 485 kN. The failure of the specimen occurred due to combined compression and bending of the concrete layer of the retrofitting system. The opening of the crack took place at the height of 100cm, where the Ø16 rebars ended. At the end of the test, wide cracks were observed in the top rib, where the forces are transferred between the floor and the concrete vertical layer. The good interlocking of the orthogonal walls and the high stiffness of the timber floor resulted in a good box behavior of the specimen. For horizontal displacement up to 3mm, the shear deformation of the piers was negligible. For higher top displacements, some small deformations occurred. At the end of the test, it was possible to observe stepped diagonal cracks at the corner of the door openings. The horizontal slip measured at the bottom of the specimen reached the maximum value of 1.5mm (Fig.6 b), so the connection with the foundation prevented the sliding at the base.

The wide and symmetric cycles in force-displacement curves (Fig.6 a) may lead to the conclusion that the proposed system has a dissipative behavior. However, the dissipative capacity that the system showed is only due to the deformation of the connection steel bars at the base between the concrete layer and the foundation. The rigid rocking highlighted the uplift of the concrete membrane with respect to the foundation. The displacement capacity is due to the deformation of the unconfined portion of the bars at the base. Therefore, the system cannot be classified as ductile and dissipative, and a non-dissipative elastic calculation is recommended.

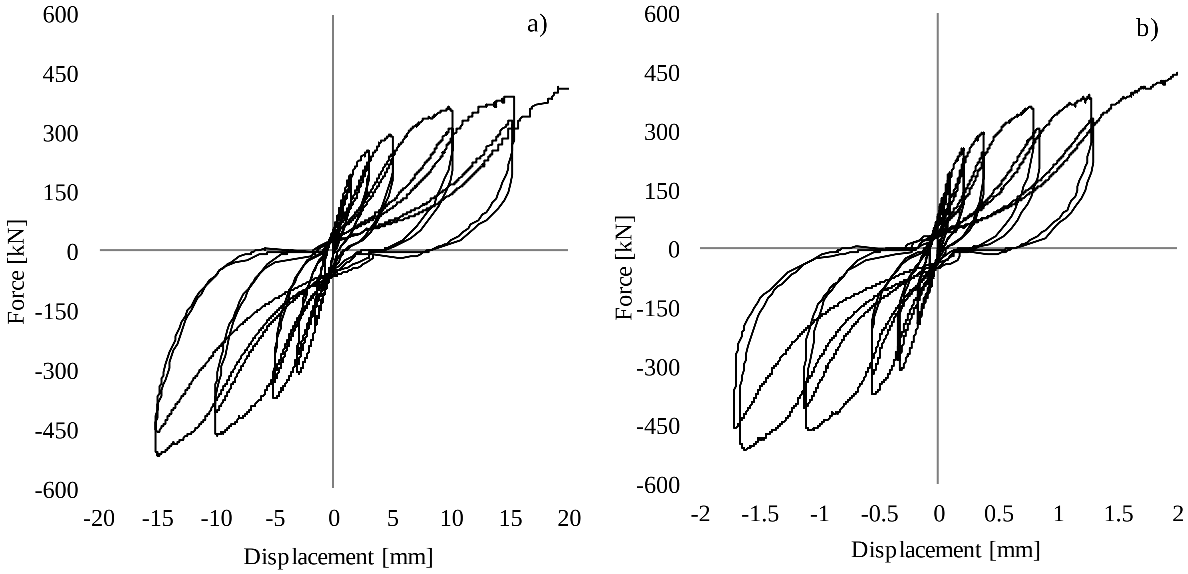

Fig.6 – a) Force–top-displacement curve measured at the top of the concrete membrane
b) Force-slip curve measured at the base of the specimen

4. Case study: retrofitting of an existing concrete building

In the last few years, the Italian government put much funding to promote the retrofitting of existing buildings. A focus is the seismic safety of the public facility, in particular, the educational ones. The following sections describe the application of the proposed technology to a real building. The case-study is a secondary school located in the northeast of Italy. The region is classified as medium-high seismicity with a PGA equal to 0.205g. The objective of the retrofitting was to reduce the energy consumption by turning the building in near-zero energy building and to increase the seismic safety to a ratio capacity/demand equal to 0.8.

4.1 Description of the existing structure

The case study building is an RC structure. The building was realized in two blocks, the first in 1971 and the second in 1979 (highlighted with the red line and the blue line respectively in Fig.7). Block 1 consists of the classrooms and teacher offices that are connected by a service area with locker rooms to the gym. Block 2 consists of additional classrooms, the auditorium, and the music laboratory. The two blocks are composed of respectively four and three sub-blocks separated by construction joints.

Block 1 was designed according to pre-70's practice when capacity design and seismic detailing were not yet introduced. The structural system consists of RC frames aligned only in the longitudinal direction; in the transversal direction, there are no structures that can resist horizontal loads. Sub-blocks C1 and C2 have two stories above ground and one story partially underground, with a total height of 9.5m above ground; sub-block A (the gym) has one story with a total height of 7.3m, and sub-block B is one-story with a total height of 3.8m.

Block 2 was built after the first Italian seismic regulation ("Legge n. 64 del 2 Febbraio 1974"), with the first specifications about seismic detailing. Being more recent, it presents an improved structural system that consists of RC frames with better characteristics of materials and a higher geometric reinforcement ratio. Block 2 is one-story with a medium height of 4.5m. Sub-block D frames had double beams due to flat roofs at different height connected to the same frame.

The aim of the structural reinforcement was to achieve a capacity over demand ratio equal to 0.8. Due to the building complexity and irregularity in plan and elevation, various technologies were used to reach the target. More specifically, for Block 2, the seismic retrofitting was pursued with steel bracing positioned to recalibrate the center of stiffness with the center of mass, in order to reduce the torsional effect. In Block 1, for sub-blocks A, C1, and C2, the retrofitting technology studied in this work was applied. For the sake of brevity, in the following sections, only the design of sub-block C1 and C2 is reported.

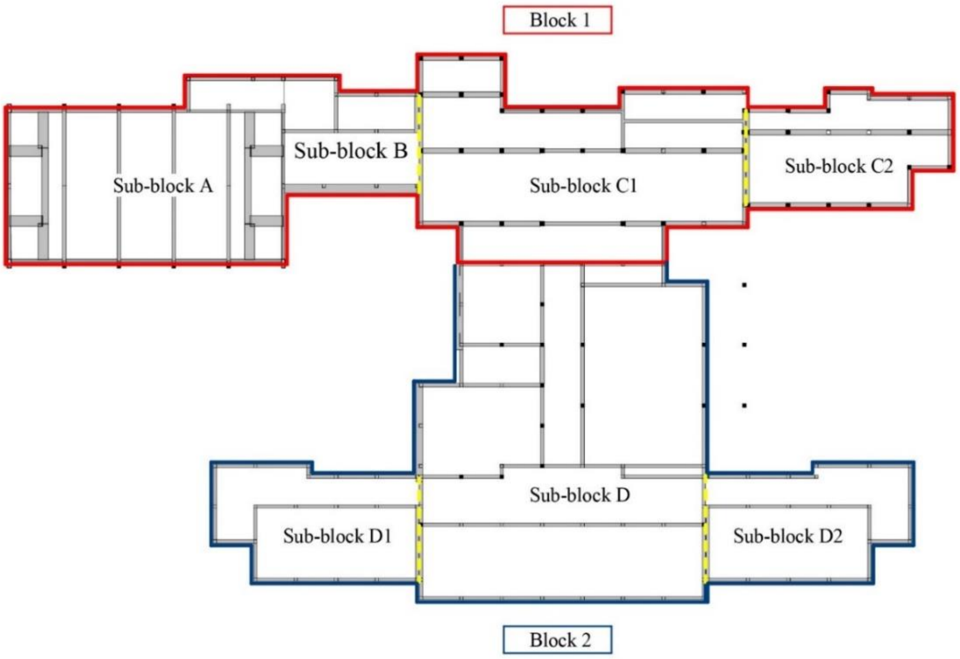

Fig.7 – Definition of Block 1 (red) and Block 2 (blue)

4.2 Frame geometry, section details, and material properties

In the present and following sections, Sub-blocks C1 and C2 are considered as a single building, regardless of the other structures of the building. The plan dimensions are 49x13m. The interstory height of the underground level is 3.3m, and of the ground and first level 3.8m. The building structural system consists of reinforced concrete frames parallel to the longitudinal direction, with 3.75m spans.

The section of the columns is 30x35cm at the basement and 30x30cm at the upper levels. All the columns are continuous from the foundation to the roof. Fig.8 shows section geometry and reinforcement details. The section of the beams is 50x23cm for the internal frame and 40x23cm for the external frames. Geometry and reinforcement details of the beams are shown in Fig.8. The RC and hollow tiles mixed floors have 20+3cm thickness, with a total thickness equal to the height of the beams. The on-site structural diagnostic campaign confirmed the structural details in the original drawings.

Some non-destructive and partially destructive tests were performed to assess the mechanical parameters of the materials employed in the existing building. Tests with hammer and crushing test of hardened concrete core samples returned the compressive strength of the concrete; tests with covermeter confirmed the presence of the rebars indicated in the drawings, and tensile tests on metal bars extracted from columns gave the tensile strength of the rebar steel. Table 1 lists the values assumed for the existing material properties. For the structural layer of the retrofitting technology, concrete of class C25/30 and steel of class B450C were used, according to the Italian building design code. The mechanical properties are shown in Table 2.

Characteristic resistance values must be divided by the partial factor for materials γ_M and the factor related to the knowledge of the existing structure FC to obtain the design resistance for the verification of brittle mechanisms. For the verification of ductile mechanisms, the application only of the factor FC is sufficient to obtain the design resistance.

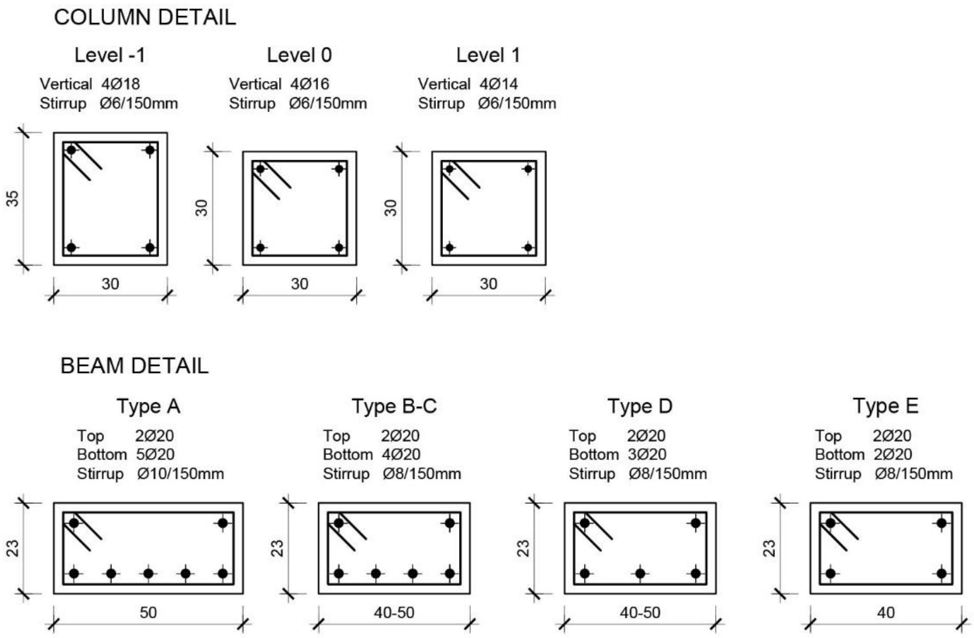

Fig.8 – Cross-sections of beams and columns

Table 1 – Mechanical parameters of existing materials

Material	Class	Type	f_k [MPa]	E [GPa]	FC	γ_M
Concrete	Rck300	Existing	28.6	30	1.2	1.5
Steel	Aq50	Existing	270	210	1.2	1.15

Table 2 – Mechanical parameters of new materials

Material	Class	Type	f_k [MPa]	E [GPa]	γ_M
Concrete	C25/30	New	25	30	1.5
Steel	B450C	New	450	210	1.15

4.3 Numerical structural analysis and design

A numerical 3D finite element model of the structure was built using the commercial code Midas Gen. The aim of the numerical analysis is first assessing the vulnerability of the actual state of the structure and then designing the retrofit to improve the seismic safety of the building. The existing RC frames are modeled with beam elements with the geometry and materials specified in the previous Sections. The RC layer of the integrated retrofitting system is modeled with plate elements with the actual thickness and the aforementioned material properties. The infill and the partition walls were not modeled but were taken into account in terms of mass. The new earthquake-resistant structure and the RC frame structure are linked with vertical and horizontal truss elements. The truss elements are useful to design the diameter and the number of the fasteners to transfer the horizontal loads from the existing structure to the earthquake-resistant new one.

Loads are defined according to the floor destination, following Italian provisions about loading conditions [9]. The FE model is conceived to assign the vertical static loads only to the existing structure. Due to its geometry conception, the proposed retrofitting technology resists only horizontal loads. Conservatively, its contribution to the vertical load resistance has not been taken into account.

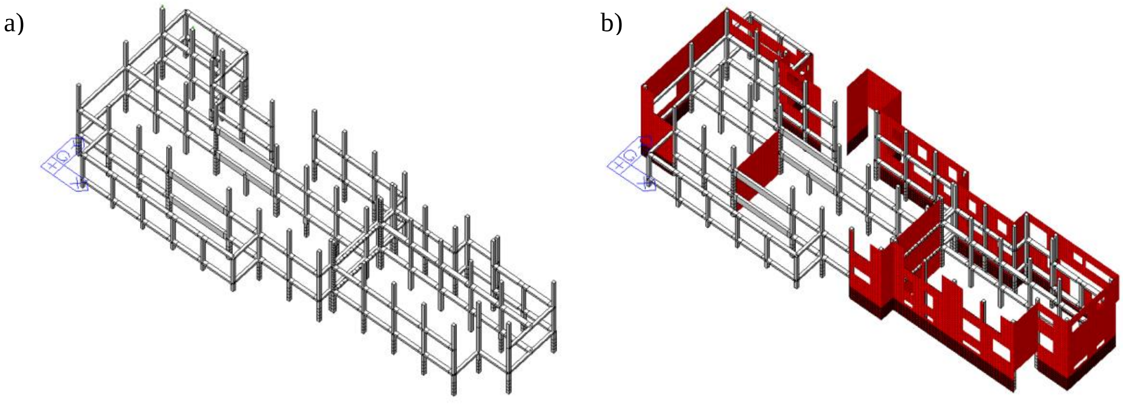

Fig.9 – Numerical model of the actual structure (a) and retrofitted structure (b)

The aim of the structural reinforcement was to achieve a capacity over demand ratio equal to 0.8. Due to the building complexity and irregularity in plan and elevation, various technologies were used to reach the target. More specifically, for Block 2, the seismic retrofitting was pursued with steel bracing positioned to recalibrate the center of stiffness with the center of mass to reduce the torsional effect. In Block 1, for sub-blocks A, C1, and C2, the retrofitting technology studied in this work was applied. The construction joint between Sub-block C1 and Sub-block C2 has been seamed by the new continuous concrete membrane applied on the outer of the building. As can be seen in Fig.9, in this particular case study, the shape of the building requires the construction of two internal RC walls to resist the seismic load in the Y direction. For the sake of brevity, in the following sections, only the design of sub-block C1 and C2 is reported.

First, a modal response spectrum analysis was performed for the existing structure. Due to the low thickness of the concrete layer of the floor structure, the hypothesis of the rigid diaphragm is not valid (less than 40mm according to the Italian design code [9]). The flexible floor, then, causes the amplification of stresses in the peripheric columns. The construction joint between Sub-body C1 and Sub-body C2, which allows independent displacement between the two parts, proved to be not sufficient to prevent hammering effects.

The new earthquake-resistant walls are continuous from the foundation level to the roof and are connected to the edge beams of each story and to the external columns. The thickness of the RC layer of the reinforcing system is equal to 150mm. Modal analysis was performed on the retrofitted structure, which has a higher stiffness with respect to the RC frames. As a consequence, the vibration period of the building decreases, and the seismic action increases (Fig.10).

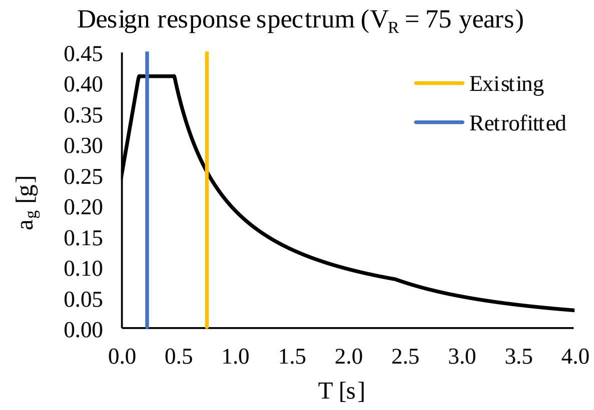

Fig.10 – Design response spectrum

After the retrofit, the stress in the existing RC frame is drastically reduced, because most of the seismic load goes to the new concrete membrane due to its high stiffness. The increment of the seismic load is compensated by the higher strength of the new structure, designed according to the current design code specifications. A positive effect of the global stiffening of the structure is the decrease of the displacements, with the consequent decrease in deformations of the existing structures.

Table 3 – Modal response spectrum analysis results

Model	**Mode**	**Principal direction**	**Frequency [Hz]**	**Period [s]**	**Mass ratio [%]**
Existing	1	Tran-Y	1.338	0.748	71.65
Existing	2	Rot-Z	1.558	0.642	55.26
Existing	3	Tran-X	1.768	0.566	53.72
Retrofitted	1	Tran-Y	4.624	0.216	81.27
Retrofitted	2	Tran-X	7.434	0.135	74.70
Retrofitted	3	Rot-Z	8.427	0.119	80.04

5. Conclusions

Most of the building stock in Europe have high energy consumption due, among other causes, to the lack of thermal insulation of the building envelope. The same buildings have been built when the design codes did not contain seismic provisions, resulting in a high vulnerability. Integrated retrofitting solutions can improve both the energy and seismic performance of existing buildings and constitute and efficient and cost-effective solution.

In this work, the application of an integrated retrofitting technology to a one-story masonry building is presented. A quasi-static cyclic load test was performed to assess the behavior of the reinforced building. The specimen presented satisfactory strength and a brittle failure mode. The proposed reinforcing system is then classified as no-ductile, and anelastic calculation procedure is recommended.

The application of the proposed technology to a real case-study is then presented. The studied building had an RC frame structure. Due to the complexity and irregularity of the structure, different structural intervention has been put in place, in order to achieve the desired seismic performance level. Part of the structure was retrofitted with the integrated retrofitting system, leading to an increased global stiffness and strength of the building and to a reduction of the stress in the existing structural elements. The global displacements of the existing structures have also been reduced. The integrated retrofitting technology showed to be an effective solution for improving the seismic performance of complex buildings.

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