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THE INTEGRATED STRUCTURAL, ENERGETIC AND ARCHITECTURAL APPROACH FOR SUSTAINABLE REQUALIFICATION OF REINFORCED CONCRETE BUILDINGS

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ABSTRACT

The prevalent aptitude to tackle the lacks in the energetic, structural and architectural field of existing buildings is today sectorial and without a real coordination between several disciplines, defining options that are episodic and limited to the resolution of isolated and temporary matters. The state of art, in fact, highlights the general tendency to treat separately these themes in the context of rehabilitation of existing building and it is observed the rarity of integrated measures that suggest, through only one solution, an improvement of structural and energetic performances, conferring, in addition, an architectural quality. Among the examples about measures for building improvement and requalification through an integrated approach there are few cases that suggest the introduction of an external skin, able to improve not only the architectural quality of the building but also the energetic performance, thanks to a general reduction of thermal losses through its external surfaces and that has a structural function, absorbing and dissolving horizontal loads. The intervention described in this paper is applied to modern reinforced concrete buildings, dating from the second postwar and located in Italy. The solution here presented is validated by structural and energetic simulations and the improvements of the building with the double skin façade are analysed both in terms of anti-seismic response, using FEM codes, and of energetic modelling in a dynamic regime.

Keywords: Sustainable seismic retrofit; Engineered double skin façade; Integrated structural and energetic measures.

1. INTRODUCTION

In the last decades, an economy centred on a general reduction of the energetic consumption and CO2 emissions has dictated important changes in every sector and especially in the world of constructions.
Since buildings are responsible for the 40% of the total energetic consumption and cause at least the 36% of the greenhouse gas in Europe, the minimum energetic requirements for new buildings and standards for the upgrade of the existing ones have been defined.
The EU Energy Performance of Buildings Directive (EPBD) in 2002 for the first time considers the impact that buildings have on the environment and identifies some values of energetic consumption and gas emissions that in the following years have become more restrictive, ensuring a better quality of life for new generations.
If the energetic performance of the existing buildings is a key element for the mitigation of the climatic change and for the definition of new strategies addressed to their containment under specific limits, the recent seismic events have underlined the structural unsuitableness and the seismic vulnerability of the existing heritage. A large percentage of the existing buildings has been built before the first anti-seismic

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laws that appeared in Italy around 1974 and the consequence of this aspect is that the number of buildings not designed or verified for seismic actions is high. In addition, a lot of them have exhausted the estimated life that is around 50-60 years [1].
A holistic approach could be today a successful choice, thanks to a combined intervention for the improvement of the energetic and structural performance able to overcome the above mentioned lacks.
The present study is focused on the use of an engineered double skin façade for the energetic, structural and architectural rehabilitation of existing buildings that are part of the Italian social housing scenario and that have been built after the second post-war.

2. THE DOUBLE SKIN FACADE AS INTEGRATED SOLUTION: THE STATE OF ART

In light of evident structural, energetical and architectural lacks the general tendency is solving each set of problems working in a sectorial way and without a common coordination among different disciplines. From the analysis of the state of art, in fact, it is evident that the suggested solutions, in most cases, define options that are episodic and limited to the resolution of isolated and temporary matters, although they are in some cases technologically advanced. In this scenario, some interventions for the rehabilitation of residential buildings consider the use of a double skin façade (DSF) that is a second technological layer located on the outer surface of the existing building.
This new technology is able to improve both the architectural aspect and energetic efficiency of the building, as it happens with the traditional double skin façade, and its structural performance.
Among the few interesting examples in this field, there are the typologies of double skin façade designed by the University of Bergamo and Brescia, the adaptive exoskeleton of the University of Trento and the double skin used as Mass damper studied by the Yale University.
The engineered double skin analysed by the University of Bergamo and Brescia takes into account two different configurations thanks to the possibility to consider the exoskeleton made of shear walls or exploring a shell behaviour for the new façade.
In the shear walls solution, the structural improvement is totally entrusted to shear walls and the improvement of the energetic performance is ensured by the thermal insulation that covers the walls.
In the shell solution, instead, the shape and the extension of the new façade are analysed in order to decrease the area of every single structural component, loading as little as possible the foundations and the thinner parts of the exoskeleton.
Both the shear walls and the shell solution can be designed in contact to the existing structure or can be jutting, defining in this way new closed spaces related to residences or opened areas as, for example, loggias and greenhouses, on one or more than one side and variable in length according to the possibility.
Both solutions, in addition, can be designed as dissipative or not, by controlling the seismic performance of the building and dissipating it through new devices inserted in the first case or, on the contrary, by putting overstrength elements able to limit the displacements of the structure and to resist to the seismic forces in the second case [1, 2].
The solution of double skin analysed by the University of Trento has been inspired by the Biomimicry because, considering the animal world, it suggests an auxiliary structure, the exoskeleton, that, introducing a higher stiffness and a new dissipative capacity, ensures the primary structure to horizontal loads that have not considered during its design and its structural analysis.
The suggested structural skeleton more than being changeable in size, extension, typology and technology, can be designed in order to have an adaptive behaviour, considering that it can be in static condition structurally independent to the existing building and can collaborate when the load conditions require an additional strength as it happens during an earthquake.
Passive dissipative devices made of memory shape metals, strategically located and used as connectors between the new and the existing structure, decrease the horizontal displacements during the seismic events [3].
The last example that is interesting to analyse is the hypothesis studied by the School of Architecture of the University of Yale that uses the double skin façade as a system for the control of the displacement for tall buildings. Two strategies are investigated.
In the first scheme, the connectors between the inner layer and the external one are designed in order to have low axial stiffness with a damping mechanism, reducing the mechanical movement of the main

building; in the second scheme small additional masses are inserted inside the cavity of the double skin operating as Tuned Mass Dampers (TMDs).
If the two configurations are studied in detail it is clear that the main element of the first solution is the design of connectors that have to be very flexible between the external skin of the façade and the existing one, in the perpendicular direction to the sides of the building in order to decrease the horizontal dynamic load. The stiffness of the connectors in the other two directions parallel to the façade is the same of the other systems that are present on it. Consequently, as result of this addition, the external layer of the double skin is able to move forward and back but the vibration of the main structure that is enclosed by the inner layer is significantly reduced.
In the second scheme, instead, the external skin of the façade is fixed, as it happens for the conventional system of double skin façade. The innovation stands in the addition of tuned mass dampers (TMDs), for the control of vibrations of the building under dynamic loads effects [4].
Other examples of the use of the double skin façade for the structural safety and the energetic efficiency are the options analysed by Zhang and Fu [5] and the integrated façade engineering validated by Toru Takeuchi, Yasuda and Iwata [6].

3. THE CASE STUDY

The present study wants to analyse possible solutions that can be used for social housing buildings dating from the second Italian postwar.
This typology of buildings is inadequate from a structural and energetic point of view and has poor architectural quality.
The selected building has a rectangular shape with sizes equal to 22 metres x 11.5 metres and it is made of four levels above ground for a total high equal to 12.2 metres. The whole building has a residential function.
Its main axis direction is inclined towards the East-West directrix of around 53°.
Figure 1 and 2 show the architectural map and a structural section of the building.
The building has a reinforced concrete structure and infills made of hollow bricks. Hollow-core concrete slabs are present.
In detail, the used concrete has a strain class equal to C20/25 and the steel of the reinforcements is FeB32k.

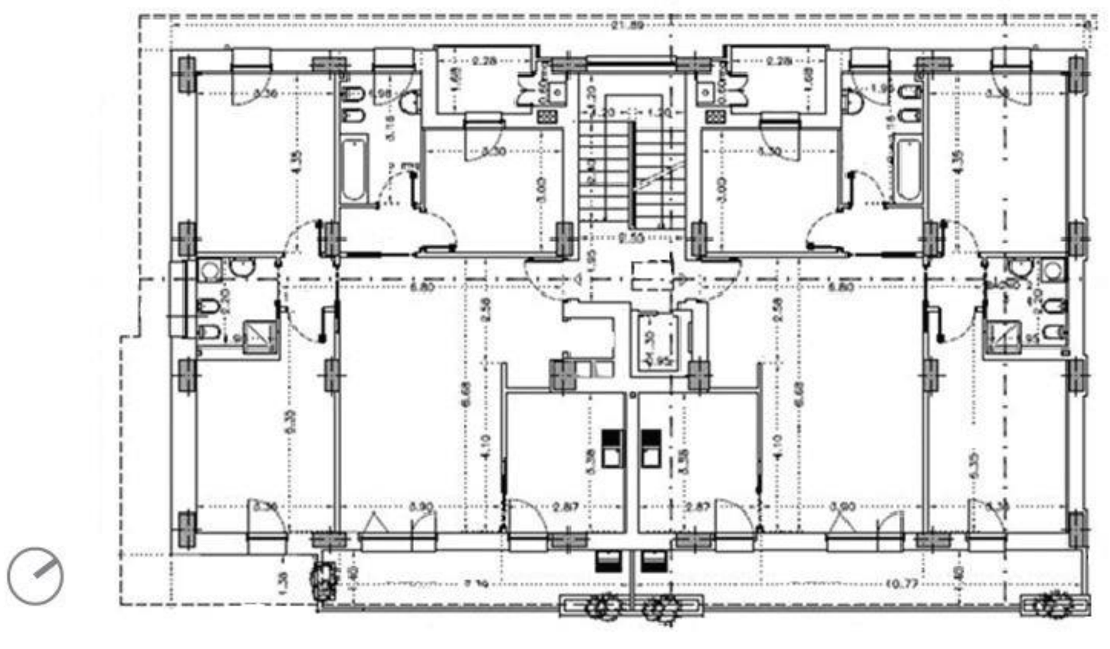

Figure 1. Architectural map of the building

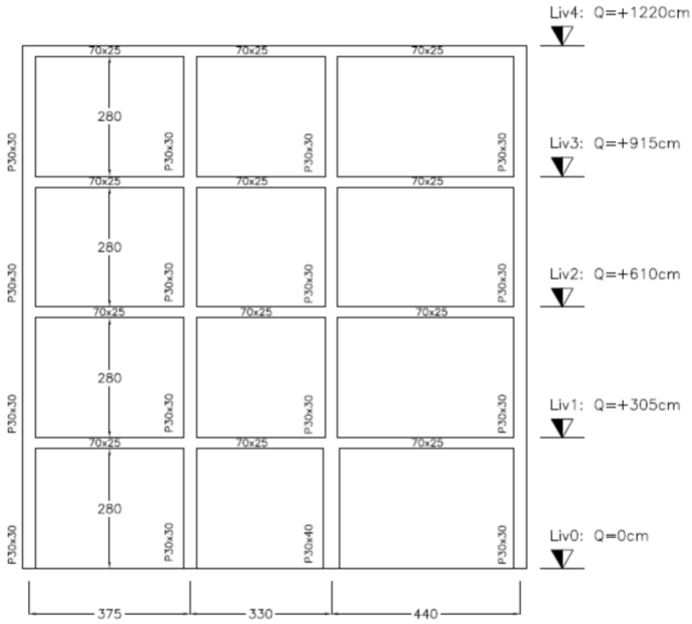

Figure 2. Section of the building

The infills, made of bricks with 12 and 8 centimetres depth and a 10 centimetres cavity, has a transmittance value (U) equal to 1.13 W/m²K and the concrete slabs, with 8 centimetres screed and floor, in addition to the structural depth equal to 25 centimetres, have an U value equal to 1.40 W/m²K.
The glassed surface occupies 12% of the total surface and the windows have a double glass with aluminium frame without the thermal break. They have an U value equal to 3.16 W/m²K.
The plant system of the building is made of a system for the heating and cooling of internal spaces and for the production of hot water. These plants are quite old and with low energetic efficiency.
There are, in fact, natural gas boilers with a coefficient of performance around 85% and split system for the cooling with a COP equal to 1.8.
The case study has been analysed through two different models: a structural model for the linear and not linear analysis using the software Midas Gen and a model for the dynamic simulation in Energy Plus to evaluate the energetic performance.
The typology of double skin façade analysed in this study and chosen for the structural and energetic improvement of the existing building is not ventilated and multiple storeys. It means that the cavity between the inner and the outer layers of the DSF is not open and it extends over the total height of the building and without a separation at the single stories.

4. THE ENERGETIC MODELLING

4.1 Adopted modelling criteria

On the base of architectural and structural information about the building adopted as the case study, a model for the energetic simulation has been made by using the software DesignBuilder, a graphical and user-friendly interface of Energy Plus.
Using this software the geometry of the building has been defined; the balconies, important for the shading system of the lower spaces and present on the South façade, have been modelled using the component block; the characteristics of the external and internal surfaces of the building have been inserted and also information about the activities of the internal spaces and the type of plants that are present have been added.
Once the state of being has been analysed and the lacks have been underlined, some possible

configurations of double skin façade have been studied.
The double skin façade that has been chosen has structural elements made of steel material and triple glass having a low value of transmittance (U= 0.79 W/m²K) for the external layer.
There are some important considerations when DesignBuilder is used to model passive double facades. Firstly, the Zone type on the Activity tab should be set to Cavity at zone level in the cavity zone and this causes the following further changes to be made to the model: the zone is set as unoccupied by loading, HVAC and Lighting template data; the Cavity internal convection algorithm is set for Cooling design, Heating design and simulation calculations to correctly model the air space; the full interior and exterior Solar distribution algorithm is set for Cooling design and Simulation because it allows solar radiation to be accurately transmitted through the interior glazing in the partition.
The performances of double skin with different air cavities have been as the first stage analysed.
The considered cavity has been 1, 1.5, and 2 metres that are the values frequently encountered in the state of art for projects with the same technology.
The double skin has been alternately located on the North-West and South-Est façade.
Subsequently, shading systems with different size and typology have been inserted for each configuration. The two external shading systems used in this study have been louvres with the main dimension equal to 0.5, 1 and 1.5 metres and blinds with low reflectivity slats.
After defining the best configuration for each façade (North-West and South-Est) the building has been enclosed using an exoskeleton on both sides.
The energetical performances have been evaluated, both for the state of being and the project, supposing two different Italian locations, Messina and Bergamo, opposite because of climatic conditions, in order to define the behaviour of this technology in hot and cold climates.
Messina is, in fact, classified as climatic zone B and Bergamo is in E climatic zone.

4.2 Results and comparisons

The following results are referred to the energetic consumption for the heating and the cooling of the inner spaces, for the state of being and for the different configurations of double skin facades (North-West and South-Est exposition, with variable air cavity and with external shading system with different size and typology) both for the cold climate (Bergamo) and the hot one (Messina).

Table 1. Energetic consumption of the state of being in cold climate (Bergamo)

DSF Typology	Heating [kWh]	Cooling [kWh]	Tot [kWh]
No DSF	63,819	6,519	70,338

Table 2. Energetic consumption of the building with DSF in cold climate (Bergamo)

DSF Typology	Heating [kWh]	Cooling [kWh]	Tot [%]
DSF_North-West Esposition			
DSF(1.0 m cavity)	53,133	15,252	-2.8 %
DSF(1.5 m cavity)	53,341	16,406	-0.8 %
DSF(2.0 m cavity)	53,785	16,351	-0.3 %
DSF(1.0 m cavity, 0.5 m louvres)	54,138	12,709	-4.5 %
DSF(1.5 m cavity, 0.5 m louvres)	54,313	13,899	-3.0 %
DSF(2.0 m cavity, 0.5 m louvres)	54,768	13,889	-2.4 %

DSF(1.0 m cavity, 1.0 m louvres)	55,212	10,276	-6.9 %
DSF(1.5 m cavity, 1.0 m louvres)	55,356	11,494	-5.0 %
DSF(2.0 m cavity, 1.0 m louvres)	55,821	11,540	-4.2 %
DSF(1.0 m cavity, 2.0 m louvres)	55,668	9,350	-7.6 %
DSF(1.5 m cavity, 2.0 m louvres)	55,795	10,555	-5.7 %
DSF(2.0 m cavity, 2.0 m louvres)	56,261	10,626	-4.9 %
DSF(1.0 m cavity, external blinds)	54,517	6,625	-13.1 %
DSF(1.5 m cavity, external blinds)	54,671	7,515	-11.6 %
DSF(2.0 m cavity, external blinds)	55,116	7,603	-10.8 %
DSF_South-Est Esposition			
DSF(1.0 m cavity)	52,943	15,257	-3.0 %
DSF(1.5 m cavity)	53,381	15,711	-1.8 %
DSF(2.0 m cavity)	53,978	15,325	-1.5 %
DSF(1.0 m cavity, 0.5 m louvres)	54,683	11,772	-5.5 %
DSF(1.5 m cavity, 0.5 m louvres)	55,054	12,352	-4.2 %
DSF(2.0 m cavity, 0.5 m louvres)	54,768	12,143	-3.6 %
DSF(1.0 m cavity, 1.0 m louvres)	56,703	9,140	-6.4 %
DSF(1.5 m cavity, 1.0 m louvres)	56,979	9,816	-5.0 %
DSF(2.0 m cavity, 1.0 m louvres)	57,522	9,758	-4.3 %
DSF(1.0 m cavity, 2.0 m louvres)	57,681	8,126	-6.4 %
DSF(1.5 m cavity, 2.0 m louvres)	57,898	8,821	-5.1 %
DSF(2.0 m cavity, 2.0 m louvres)	58,421	8,822	-4.4 %
DSF(1.0 m cavity, external blinds)	54,735	6,366	-13.1 %
DSF(1.5 m cavity, external blinds)	55,104	6,937	-11.8 %

DSF(2.0 m cavity, external blinds)	55,682	6,984	-10.9 %

Table 3. Energetic consumption of the state of being in hot climate (Messina)

DSF Typology	Heating [kWh]	Cooling [kWh]	Tot [kWh]
No DSF	14,390	18,601	32,991

Table 4. Energetic consumption of the building with DSF in hot climate (Messina)

DSF Typology	Heating [kWh]	Cooling [kWh]	Tot [%]
DSF_North-West Esposition			
DSF(1.0 m cavity)	9,281	28,920	+15.8 %
DSF(1.5 m cavity)	9,322	28,671	+15.2 %
DSF(2.0 m cavity)	9,384	28,863	+15.9 %
DSF(1.0 m cavity, 0.5 m louvres)	9,954	25,169	+6.5 %
DSF(1.5 m cavity, 0.5 m louvres)	10,013	24,956	+6.0 %
DSF(2.0 m cavity, 0.5 m louvres)	10,102	24,693	+5.5 %
DSF(1.0 m cavity, 1.0 m louvres)	10,751	21,606	-1.9 %
DSF(1.5 m cavity, 1.0 m louvres)	10,837	21,489	-2.0 %
DSF(2.0 m cavity, 1.0 m louvres)	10,949	22,281	+0.7 %
DSF(1.0 m cavity, 2.0 m louvres)	11,113	20,238	-5.0 %
DSF(1.5 m cavity, 2.0 m louvres)	11,198	20,153	-5.0 %
DSF(2.0 m cavity, 2.0 m louvres)	11,324	19,999	-5.1 %
DSF(1.0 m cavity, external blinds)	9,512	16,437	-21.3 %
DSF(1.5 m cavity, external blinds)	9,563	16,362	-21.4 %
DSF(2.0 m cavity, external blinds)	9,645	16,378	-21.1 %
DSF_South-Est Esposition			
DSF(1.0 m cavity)	8,923	30,571	+19.7 %

DSF(1.5 m cavity)	9,064	29,905	+18.1 %
DSF(2.0 m cavity)	9,245	29,172	+16.4 %
DSF(1.0 m cavity, 0.5 m louvres)	10,078	25,228	+7.0 %
DSF(1.5 m cavity, 0.5 m louvres)	10,216	24,782	+6.1 %
DSF(2.0 m cavity, 0.5 m louvres)	10,406	24,288	+5.2 %
DSF(1.0 m cavity, 1.0 m louvres)	11,569	21,067	-1.1 %
DSF(1.5 m cavity, 1.0 m louvres)	11,706	20,838	-1.4 %
DSF(2.0 m cavity, 1.0 m louvres)	11,895	20,522	-1.7 %
DSF(1.0 m cavity, 2.0 m louvres)	12,373	19,428	-3.6 %
DSF(1.5 m cavity, 2.0 m louvres)	12,500	19,288	-3.6 %
DSF(2.0 m cavity, 2.0 m louvres)	12,690	19,077	-3.7 %
DSF(1.0 m cavity, external blinds)	9,304	17,126	-19.9 %
DSF(1.5 m cavity, external blinds)	9,457	16,949	-20.0 %
DSF(2.0 m cavity, external blinds)	9,652	16,787	-19.9 %

The results obtained by the energetic simulations underline in a clear way that, regarding the cold climate, the introduction of a double skin on the South-Est façade is the best choice, ensuring a reduction for the heating load of 17%. It is also evident that in the configuration of double skin, both on the South-Est façade and on the North-West one, increasing the depth of the air cavity the gain in terms of energy consumption for the heating demand decreases because there is a reduction of the internal solar gain that enters weakly the spaces behind the exoskeleton.
The study of this technology for hot climate shows that also in this case, the most convenient condition is the insertion of the double skin on the South-Est façade, ensuring a reduction of the heating loads of around 38% that is more than double of the amount that could be achieved in cold climate with the same condition.
Considering the energetic consumption for the cooling of the spaces, it is clear that for each configuration, the insert of a shading system made of external blinds with low reflectivity slats allows a significant reduction of this load.
These values would be higher with an active (ventilated) double skin thanks to the possibility to remove the volume of hot air inside the cavity just above the existing building, ensuring low energetic consumption and good comfort during the summer season.
Confronting the total energetic consumption due to the air conditioning (both cooling and heating) of the building with a double skin, the inserting of an exoskeleton in hot climates (-21%) is more useful than the same intervention in cold climates (-13%).
Defining the best configuration for each façade (North-West and South-Est) and for each climatic condition, the building has been studied considering the double skin on two of the main facades. For cold climate, double skin with air cavity equal to 1 metre and external blinds with low reflectivity slats for the North-West and South-Est façade has been chosen. For hot climate the choice, instead, has been

the topology of double skin with 1.5 metres cavity and external blind with low reflectivity slats for both expositions.

Table 5. Energetic consumption of the building with DSF (North and South façade) in cold and hot climate

DSF Typology	Heating [kWh]	Cooling [kWh]	Tot [%]
DSF_cold climate	33,269	6,300	-43.7 %
DSF_hot climate	5,262	15,117	-38.2 %

It is important to underline that the energetic consumptions that are summarised in these tables are referred not considering the efficiency of the plant system.

5. THE STRUCTURAL MODELLING

5.1 Adopted modelling criteria

The structural modelling has been carried out with the FEM code Midas Gen and using concentrated plasticity models for non-linear analyses. This schematisation concentrates the inelastic deformations at the end of the structural elements using concentrated plastic hinges and predetermined phenomenological constitutive laws. These laws may consider degrading nonlinear response through experimental calibrations based on the N-My-Mz interaction.
Shear and flexural hinges have been inserted for beams and for column hinges that consider shear and combined compressive and bending stress.
The structural details have been defined considering the typical construction practice at the time of construction. In this regard, the Rck250 concrete and FeB32k steel have been used for the analysis and their elastic modules have been appropriately reduced (70% columns and 50% beams) in order to consider their cracked condition.
The structural elements such as beams, columns and staircase have been modelled using beam elements. The balconies on the South façade have not been modelled and their presence has been considered only with their weight. The same choice has been made for the infills, implemented exclusively as a load.
For the pushover analysis, two different force distributions have been inserted, as it is suggested by the Italian code (NTC2008). As main distribution, a modal distribution of forces has been used and for the secondary distribution, a uniform distribution has been chosen. This has been done in both direction, the positive and the negative one, obtaining in total 8 load conditions.
Figure 3 graphics the two main distributions.

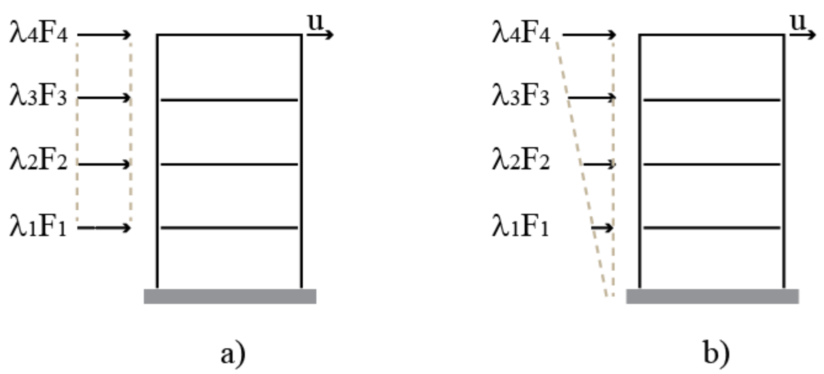

Figure 3. Force distributions for Pushover analysis: (a) unifom distribution and (b) modal distribution

In order to analyse the structural performance of the existing building and the efficacy of the studied solution in the worst seismic condition, the case study has been located in the city of L'Aquila that has a PGA value around 0.260 g.

5.2 Results and comparisons

Figure 4 shows the capacity curves of the existing structure defined in terms of base shear and displacement for each distribution of forces.

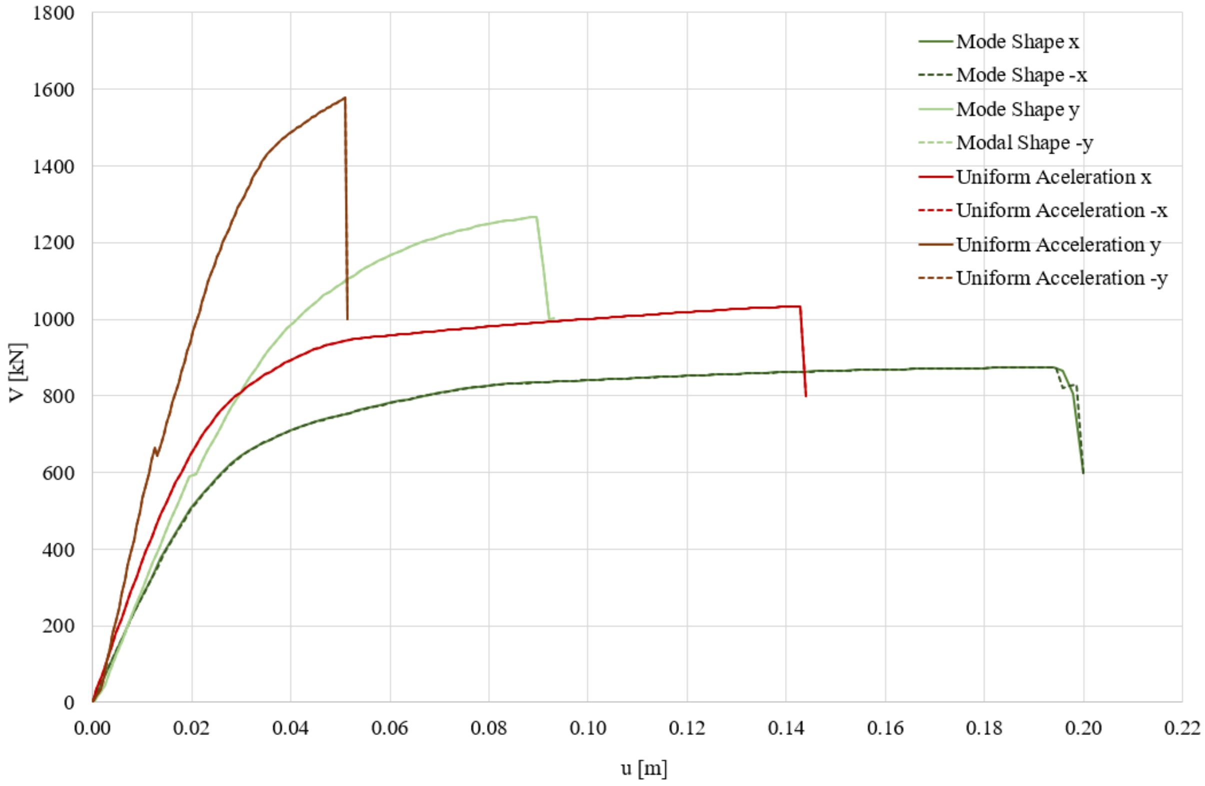

Figure 4. Pushover curves with modal and uniform distribution

Analysing the capacity curves obtained from different pushover analyses and comparing them with the ADRS spectrum, the structure is not verified for both ultimate and damage limit state. It is, therefore, a structure that has high seismic vulnerability especially along the minor side. The structural capacity is 54% of the ultimate limit state earthquake demand.

The collapse of the structure is due to flexional stresses of the elements, both columns and beams, and it is also observed the formation of shear failures located along the short columns of the staircase.

The structure is strengthen with the engineered double skin façade. The skin is made of steel and surrounds the whole building.

In detail, the Buckling-Restrained Axial Dampers (BRAD) have been inserted into the double skin, as it can be seen in Figure 5. These devices protect the structure through energy dissipation [7].

The BRADs are modelled using plastic hinges which simulate the dynamic behaviour of the devices.

A frame of dissipative braces has been localised above all sides of the building in a symmetrical way in order to avoid torsional phenomena of the main structure and a system of horizontal X braces has been inserted on the last floor.

It is important to underline that the BRAD stiffness is selected to increase the structural stiffness and therefore to limit the interstory drift at damage limit state. The BRADs used have different dissipative capacities for each level but are the same for each floor.

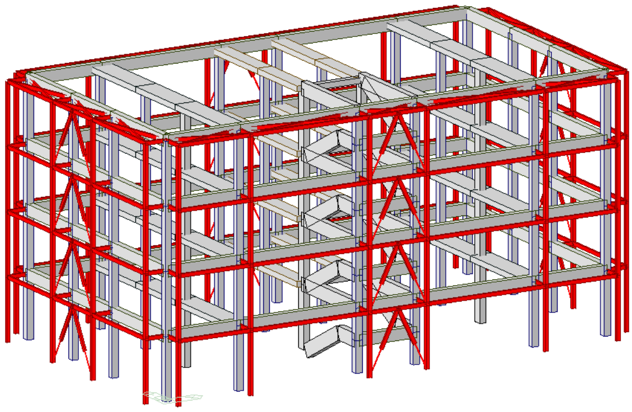

Figure 5. Model of the building with the exoskeleton

The connection between the existing building and the new structure has been designed to avoid the transfer of flexural forces. In addition to this global intervention, some local interventions are necessary for the elements subjected to shear failure. In particular, the short columns located around the staircase are confined with Fiber Reinforced Polymers in order to avoid shear failures.
The insertion of the double skin façade and the improvement of the existing building with this new technology has been deeply studied through several pushover analyses, considering different distributions of forces.
In Figure 6 the analysis with a uniform distribution in the y-direction, which is the weakest side of the building, is reported.

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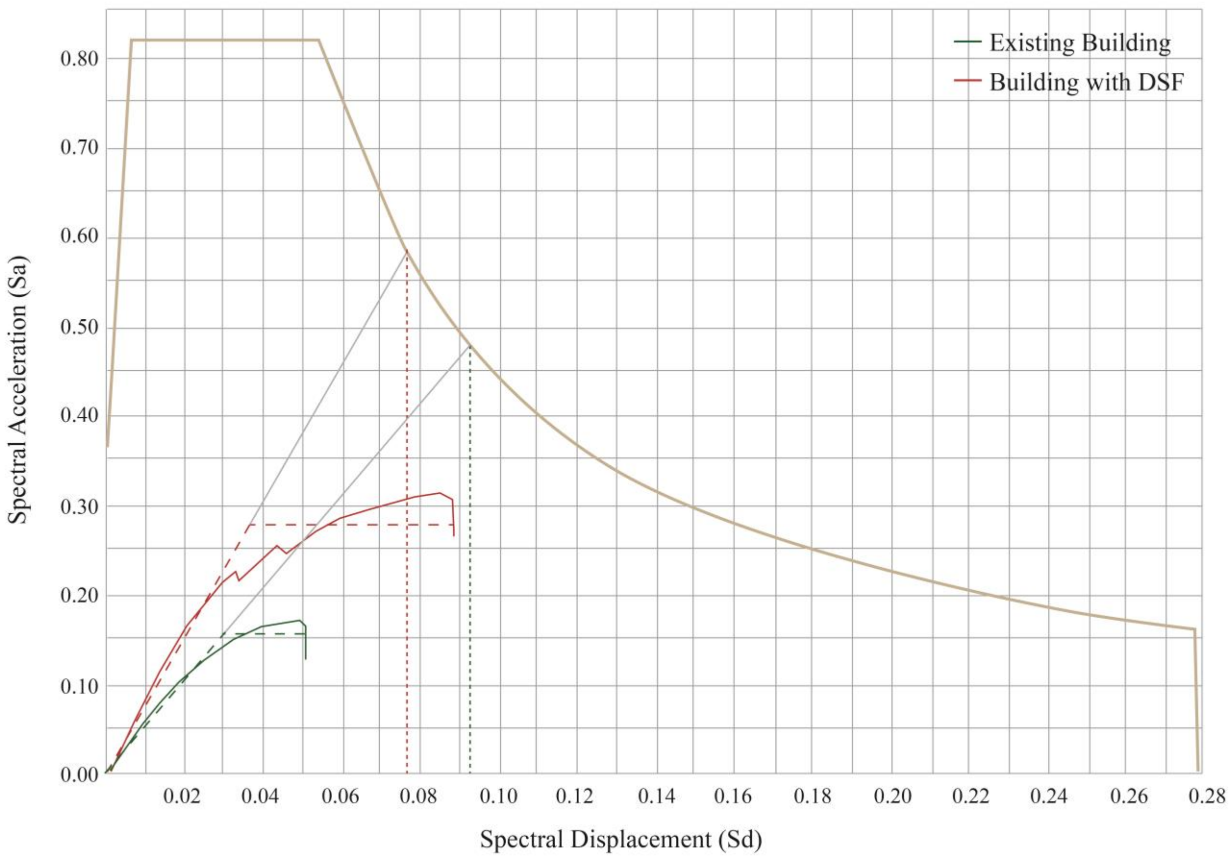

Figure 6. Capacity Spectrum and Demand Spectrum of the building with and without double skin

The results show that the insertion of the double skin façade and the BRAD dampers improve the performance and ductility of the structure.
Before the intervention the structure was not verified at damage and ultimate limit states, the insertion of the skin increased the stiffness for low intensity earthquake and increased the dissipative capacity for strong earthquakes.

6. CONCLUSIONS

Buildings with poor architectural quality and insufficient structural and energetic performances are present in Italy as in the rest of Europe in very large number and the necessity of guaranteeing an eco-efficient and resilient building stock is today relevant.
The rehabilitation of existing buildings is a real and imminent necessity and the application of an integrated retrofitting intervention which includes both seismic improvement and energy efficiency measures represents the most interesting opportunity in terms of money savings. The solution presented is able to improve the energetic and structural performance of existing buildings with minor interior interventions using an external skin.
As an additional aspect, the new external skin, made of steel and glass, could be in every moment fully dismantled, recyclable or adaptable to different and new conditions.
Both the structural and the energetic analyses show that the introduction of the double skin façade is very efficient.
From a structural point of view, the insertion of an external layer with dissipative braces ensures the retrofit of the structure. The dynamic energetic simulation underlines a reduction of the energetic consumption linked to the heating system both in cold and hot climate conditions. This is due because the double skin creates a buffer zone and reduces the thermal losses through the external surfaces. If this cavity would be also ventilated the reduction in terms of energetic consumption would be higher because it would help also during the summer season, improving the ventilation of the cavity and the expulsion of the hot air in it.

7. ACKNOWLEDGMENTS

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