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Building Exoskeletons for the Integrated Retrofit of Social Housing

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Abstract

In Europe, most of the social housing heritage, built before the 1980s, suffers of architectural and functional obsolescence and seismic vulnerability, raising questions about the future of the cities and their inhabitants. In an era of environmental emergency and lack of resources demolition and reconstruction is not a sustainable alternative. A multi-purpose campaign of architectural, functional and structural retrofit is fundamental but the complex information and requirements to handle require integrated and innovative solutions. The bio-mimicry design approach led to the definition of the “building exoskeleton”: an external steel frame, two or three-dimensional, encapsulating the existing building and provided of shape memory alloys-based devices for passive seismic dissipation. The simplicity of the structure gives high flexibility in the definition of the new architectural features and functional performances, adapting to the changing necessities on both space and time scales. The energy performances result also radically improved. The efficiency of this scheme to improve the seismic response of the constructions is verified for a real case study – a concrete frame with brick infill – through static and dynamic nonlinear analyses with the software SAP2000. Finally, the economic and technical feasibility of the proposal is discussed together with the implications of the project and the possible developments.

Keywords: Adaptive Design; Integrate Retrofit; Biomimicry; Shape Memory Alloys; Seismic Engineering; Social Housing.

1. Introduction

A consistent percentage of masonry and reinforced concrete buildings, old or recently built, cannot provide appropriate levels of seismic safety, because of the poor quality of the construction even before that degradation and aging of materials run their course [1]. An aggravating factor is that earthquakes of significant intensity occur today in areas not traditionally considered seismically risky, revealing the limits of the approaches used to classify the territory and consequently enlightening the necessity to increase the safety levels for conventional buildings everywhere [2].

Social and economic losses caused by earthquakes are not easily quantifiable but Dolce [3] estimated that in Italy the expenses associated to seismic events are around € 2-3 billion per year, still without considering the incalculable damages related to the destruction of the historical and cultural heritage. As said, some key causes are the obsolescence of buildings and their high seismic vulnerability, in conjunction with the late classification of the territory [4], but also the deficient quality control and the insufficient analysis of the degradation processes along the entire life cycle of the buildings resulted in less durability [5] and lack of a prevention program.

Vulnerable buildings are a manifestation of the vulnerability of the urban system, since the response of the city can be interpreted as the sum of the single responses of its composing elements but also because they are the expression of the attitude towards disasters and unexpected events [6-8].

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The seismic vulnerability of buildings can be reduced designing consistently with regulations and promoting a campaign of seismic rehabilitation for existing buildings [9].

Fukuyama and Sugano [10] indicated three possible strategies for seismic rehabilitation: recovering the original performances, upgrading them or reducing the seismic response of the building. The selection of the most suitable strategy depends on several factors, such as the structural typology and technology, the historical and functional importance of the building and the socio-economic issues connected with serious damages during and after an earthquake [11]. Therefore selecting the appropriate retrofit is a complex task with multiple possible choices in relation to the factors considered and their relative importance [12]. It is rare to find the “best” intervention on a general level [13], but typically the ratio between the costs and the performances achieved is determinant for the definition of the retrofit program. This is one reason for the designers to propend for integrated approaches, a single intervention that solves a complex set of problems (architectural, functional, structural): the seismic retrofitting should be realized together with renovations and refurbishments and this synergy should improve the overall characteristics of the building at the same time reducing the ancillary construction expenses. In this way, the high costs associated with seismic retrofitting could be substantially reduced.

Already Caffrey [14] defined “Intelligent” a building able to provide a “productive and cost effective environment through optimization of its four basic elements: Structures, Systems, Services, Management, and the interrelation between them”. In the same way, an “Intelligent retrofit” for existing buildings should offer an intervention that integrates all of the different performance requirements – such as structural safety, energy efficiency and architectural quality – optimizing the construction process and the expenditures.

This paper presents a specific integrate approach for retrofit of social housing buildings based on the definition of an “adaptive exoskeleton”, connected to the existing structure with shape memory alloys-based dampers (SMADs).

In the first paragraph, the problem definition and the research scope are shown, together with the design requirements and considerations. Subsequently, the design approach and the construction process will be discussed, considering the possibility of exploiting industrialized construction methods. The seismic retrofit strategy will be shown in detail, together with the result of the numerical study for an existing case study and the economic feasibility of the proposal. Finally, the scheme will be validated also in relationship to the need of new energy performances.

2. Problem Definition

The most consistent portion of social housing heritage was built before the 1980s, so in advance with respect to the introduction of the new regulations, with their specific requirements for the achievement of minimal levels of energy performances and seismic safety. Moreover, buildings have specific life cycle expectancy, generally around 50-60 years [15], after which other weaknesses, such as the obsolescence of the technical apparatuses and of the architectural characteristics, must be considered for the quality of the cities and the satisfaction of the users.

Those buildings, obsolete or approaching disuse and demolition, can be an unexpected source for new projects [16], either if demolished to make space for new constructions or if rehabilitated and reused [17].

Demolition and rebuilding is a feasible option in order to build seismically safe houses with all the modern comforts, services and performances, improving the life quality and the internal and external environment but despite that, the process has high prices in terms both of costs and of natural impacts. A research of the Preservation Green Lab [18] declared that demolition today is not a sustainable solution: it increases the ecological emergency producing residuals and wastes difficult to remove and to reuse while the subsequent reconstruction of a new “green” building requires 80 years to compensate the use of natural resources. Moreover, considering the amount of new constructions per year, usually less than 2% of the existing, sadly, the good performances of the new buildings are currently not influential in the reduction of greenhouse gas emissions. A sustainable use of the resources would be instead to requalify the existing building heritage obtaining an overall increase of the performance of 30%, with the provision also of new services and spaces [19].

The cost of the conversion is usually lower due to the presence of pre-existing elements and materials and rehabilitation takes around half of the construction time necessary for demolition and reconstruction of the same floor area, reducing for instance the financing, the effects of inflation and the risk of collateral events with the related expenses [20]. Moreover, a problem not to underestimate is the necessity of temporary relocation of all the inhabitants of the buildings.

The director of Habitech in the 2012 declared that it is possible to capitalize the money invested in retrofit in relatively short time considering for instance the consequent increase in value of the construction, the reduced energy and water consumption and the new environmental quality achieved.

In this way, the marketability of a building is improved and, in presence of seismic retrofit, the security for lives and properties, the losses reduction – in terms of building heritage but also in equipment – and the guarantee of business continuity, attract potential buyers: the correlated advantages are more significant than the retrofit expenses [21].

Tierney [22] showed how seismic rehabilitation can assume a key role in the risk mitigation and prevention of disasters considering that earthquakes are more and more random in place, time and intensity [23]. Stevens and Wheeler [24] underlined that improving the quality of the building heritage guarantees the sustainability of the construction industries and of the cities.

To maximize the achievements of the retrofit and its sustainability architectural features, energy performances, emissions reduction and structural behavior must be part of the same integrated intervention with consequent high complexity and costs.

Nuti and Vanzi [25] declared that in order to make retrofit a good investment, the ratio between costs and reduction of the risk produced should be calculated on a large scale for a long term, but despite that, a systematic campaign, on a national or regional level, has not been undertaken yet, enduring the condition of the vulnerability of the territory.

The broad scale of the intervention faces also the necessity to break the visual monotony widely imposed to the social housing districts, leaving space to individuality and variety for more vibrant and dynamic realities. The question so is still related to the design of “large projects without imposing uniformity and rigidity where variety and adaptability over time are desirable” and to how big projects can “do justice to the small scale” [26].

In this sense, a favorable aspect is that social housing is usually free of any historical and cultural constraints typical of the building heritage, allowing a broader operative margin with multiple options to consider and to apply.

A deep retrofit is of primary importance to increase the safety and the life quality of the cities: residential districts can transform from a critical part of the city to a strategic resource to revitalize it [27].

3. The Retrofit Proposal

3.1. The Design Approach

The complexity of a retrofit intervention on social housing heritage was handled through a biomimicry process and a comparison with the natural world [28] that finally led to the definition of a “building exoskeleton”.

In Nature the exoskeleton of an insect acts as the primary interface with the outside world, defining for instance the chromatic characteristics and the thermal regulation but also acting as the main structural defence for the internal apparatuses, responding and sometimes adapting to the external inputs.

"The exoskeleton acts as a detector of displacement, strain or load via special organs called sensilla, which are partly integrated into local sections of exoskeleton. These organs amplify the information for the main detector organ, which is connected to the nerve stem. The local information obtained is used to modify the exoskeleton by changing thickness, stiffness and fibre orientation depending on the situation" [29].

Additionally the exoskeleton adjusts in time in order to respond to the growth and to the development of the insect, such as a construction today should be ideally able to modify and adapt to the changing needs of the users and the environmental requirements.

To find the best physical representation of this design concept it is necessary to determinate the relationship between construction techniques and flexibility.

Researches underlined how many of the most successful flexible housing schemes rely on simple and efficient construction techniques, which facilitate future intervention, also locating the elements needing of more maintenance and control in easily accessible areas [30]. Together with reducing the constructional complexity, the structure should indeed increase the efficiency of the whole building [31], during the construction phase, during the use and finally during the renovation processes or demolition.

Dry-technologies, based on lightness and flexibility principles, give the possibility to obtain reversible interventions allowing the eventual removal critical parts, favoring durability, adaptability and sustainability. These systems provide also reduced environmental impacts during construction and at the end of the useful life of the building organism, thanks to the high percentage of recovery of the individual components.

The structure must seek a balance between efficiency and economy reducing the required amount of material [32] exploiting at best the mechanical and physical proprieties.

Consequently, the “adaptive exoskeleton” (Figure 1) is materialized as an external steel frame encapsulating the existing building to preserve its materials and elements while at the same time granting a completely new set of performances.

The exoskeleton can be, in each side of the construction, two or three-dimensional in relation to the site conditions and to the urban planning restrictions: when it reaches an appropriate thickness, it can house new spaces and functions or new accessibility schemes being able to modify completely the overall space distribution.

The new functions and services are represented by modules, which can be inserted and mounted within the frame with mechanical processes. Every module can be realized using different technologies, components and material, and the solution chosen at the design stage by the user can be modified and extended in time with a relevant reduction of maintenance costs due to the easiness of disassembly, repair and replacement.

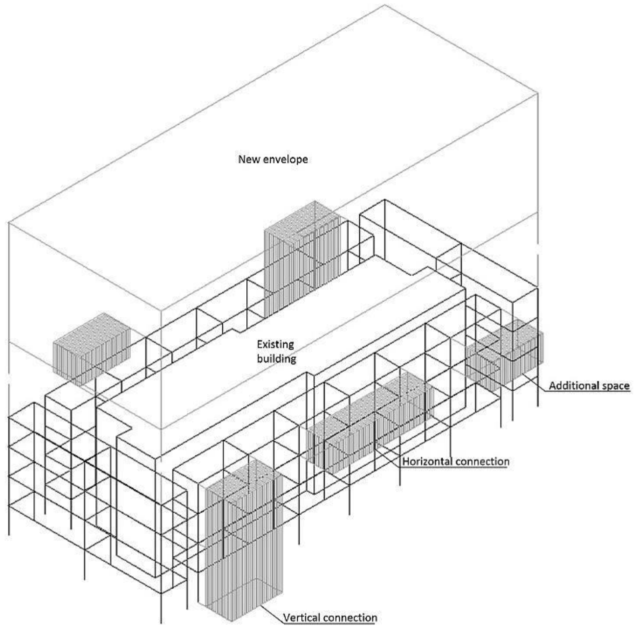

Figure 1. A scheme of the "building exoskeleton"

The reversibility and simplicity of the scheme, based on dry-construction technologies, allows multiple and progressive reconfiguration and confer a longer life span to the building in relation to changing needs of the users thus enhancing the economic value of the apartments [33]. The temporariness that characterizes the design is the most important assurance for the building to be durable in a dynamic and mutable housing market.

The quality of the structure is also expressed aesthetically [34] thanks to the vibrancy and the variety of the possible solutions, radically in opposition to monotone and impersonal traditional mass housing.

3.2. The Construction Process

The design concept directly suggests the possibility to exploit industrial construction methods, able to provide efficient and economic production allowing at the same time variety of form and solutions, since the "variety might be the logical outcome of efficient production" [35].

Industrial construction experienced a consistent growth from after the Second World War, thanks also to the new materials and technology available on the market. However, prefabrication in the housing field is still commonly unpopular due to the poor aesthetics, comfort and quality, sacrificed for fast and cheap production processes [36].

On the other hand, the standardized components, the quality assurance provided and the fast construction times granted by industrialized processes are still synonymous of achieving expected quality.

The construction industry has the potential to be the cost-effective solution to cope with the demand of housing but it must face the responsibility to provide a vibrant environment to live in, while economic reasons are no longer an acceptable excuse to justify low aesthetical quality and performances.

Moreover, if until recently the sector contributed to environmental problems by building energy-efficient buildings and using sustainable materials, soon the society will ask to justify the use of materials and energy in every phase of the lifespan of a building, including re-use of materials and re-manufacturing of components [37]. This approach implies the application of the cradle-to-cradle principle [38], so the design approach consider a careful use of the materials but also the way in which they are connected into components, with a relevant impact on the overall energy-consumption of a building [39].

The "adaptive exoskeleton" promotes also the "supply-driven demand" [40], so the suppliers will offer to the client/user a catalogue of possible options and product that fit in the system. In the same way, the user can decide to modify the dwelling during its operational life to create new or different functions; this can be done with partially disassembling/re-assembling caused modest disturbance to the user and to the neighbours.

Removed modules can be re-used in the same or in another building, or they can be disassembled into singular usable components. Since the process is dramatically dependent on joints, it is fundamental a deep design of the details [41].

3.3. The Seismic Retrofit

The seismic retrofit will consider the use of emerging technologies, since it results to be far less intrusive to building occupants and offered savings in construction cost. In addition, since no two buildings are the same, the challenge to structural select the alternative solutions that are technically, economically and socially acceptable [42].

A successful project requires the exploitation of the full potential of the technologies, of the materials and of the design; at the same time making new buildings energy and resource efficient is a core task for the current society [43].

In this respect, Peter Rice planned to use materials "to express more clearly their engineering nature, and thereby find a new and interesting aesthetic".

In this research, shape memory alloys are experimented to provide passive dissipation to seismic loads, thanks to their super elasticity, a property allowing stress-induced transformations between two crystallographic phases, completely reversible after the removal of the load for many loading cycles [44-45].

These materials has been studied for the first time in the field by for the bell tower of St. Giorgio in Trignano, Italy, [46] and in the same year for the tympanum of St. Francesco church in Assisi, Italy [47-48].

The SMADs used in this research are verified with a numerical study while laboratory tests are still needed. NiTi wires, wrapped around studs in order to work always in tension, provide tensile and compressive responses. The device was modelled with an inner and an outer tube to which studs are connected [49]. The outer studs are able to displace in both the longitudinal directions, in this way allowing the wires to work always in pure tension. This device (Figure 2), other than allowing the passive dissipation of the seismic energy, is projected for stress-induced transformation, thus providing re-centring capabilities at the end of an earthquake [50].

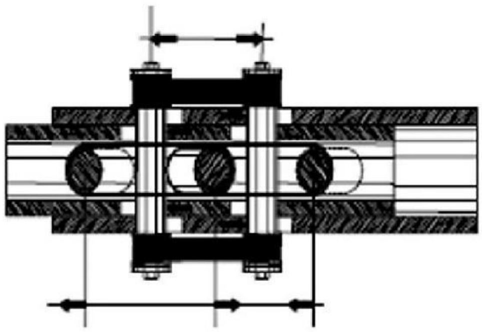

Figure 2. Dolce and Marnetto's device (2000)

The shape memory alloys dampers (SMADs) are strategically located between the new and the existing structure in order to maximize their efficiency.

The exoskeleton is built in order to be structurally independent from the existing building in relation to vertical loads, not adding any additional load and at the same time allowing to build completely from the outside, with low impact on the life of the inhabitants and no necessity for temporary relocation.

On the other hand, for horizontal loads, as in case of earthquakes, the exoskeleton activates and start to collaborate to dissipate the seismic energy thus preventing the collapse of the building (Figure 3 and 4).

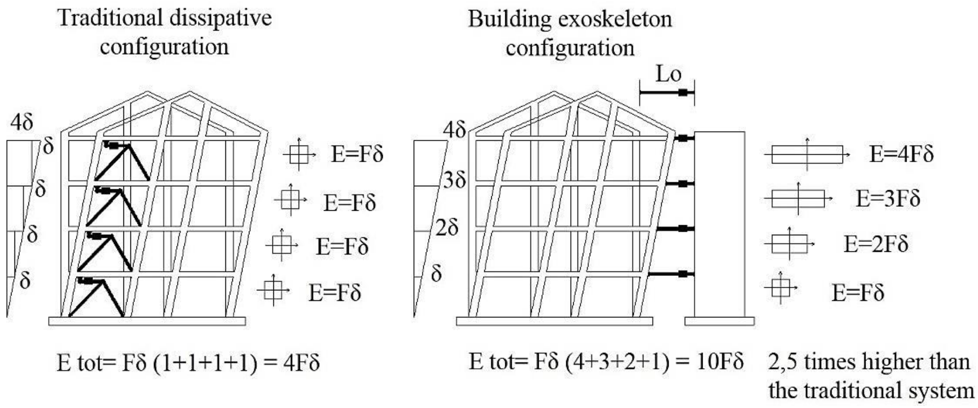

Figure 3. Localization of SMADs and comparison with traditional strategies

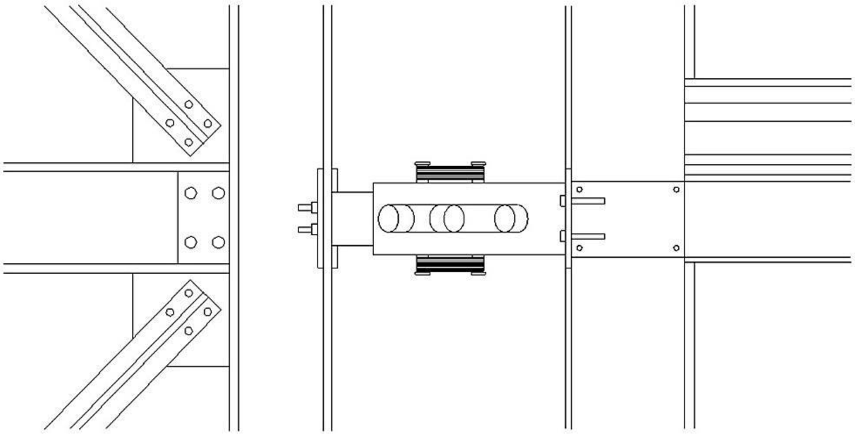

Figure 4. Schematic detail of SMAD connecting the existing building with the exoskeleton.

The frame structure provides good structural behaviour while not giving any restriction in terms of architectural characteristics: a various set of options and possibilities is feasible in relation to the environmental and cultural context of the construction site, finally giving a cost effective alternative to the facial monotony of social housing districts. The new three-dimensional envelope is also the place where the energy performance of the building can be improved through new solar protections, ventilation systems and climate control devices.

So repeatability and simple base elements, modifiable on a territorial level and on a temporal scale, where the apparent simplicity of the design is the result of a complex analysis of requirements and objective, with adaptive behaviour as the final goal.

3.3.1. A Case Study: Modeling and Results

The efficiency of the “building exoskeleton” was verified for masonry buildings and concrete framed buildings leading to promising results.

In this paper, a real case study is presented: a concrete framed building with brick infill of “Trieste” type located in Brescia (Italy), in the social housing neighborhood of San Bartolomeo.

Infill walls and panels are commonly encountered in existing buildings around the world and in regions of low to moderate seismicity.

When the infill is built in contact with the frame, it strongly influences the seismic response of the building: with the increase of horizontal loads, the panels progressively detach from the frame with horizontal and vertical relative displacements starting to act as equivalent diagonal struts. In this phase is reasonable to model the structure as a frame with diagonal braces with pure compressive behaviour. The prevalent stresses in the infill are normal compressive stresses in correspondence of the corners of the panels, still in contact with the frame, while shear stresses are less influential also because of the X-shaped fractures, typical of shear failure for alternate cyclic seismic loadings. Masonry infill of this type can enhance the lateral stiffness and the resistance to lateral loads, with a noticeable increase in energy dissipation through the formation of X-shaped fractures.

The loads distribution can also be substantially different from case of a bare frame, generating unpredictable solicitations and, subsequently, results.

The presence of infill is not always favourable so not considering its presence can lead to destructive effects such as:

- The formation of soft story mechanisms caused by the irregular vertical pattern of the panels;
- The detachment and consequent fall of the panels;
- The localized brittle failure of structural elements due to irregular openings in the panels;
- The failure of structures with regular plan distribution but with irregular infilling arrangement;
- The formation of plastic hinges in the columns for the high tensile stress caused by the panels.

The literature presents numerous studies about this topic but in this research, Al-Chaar’s considerations [51] are used to define the geometric characteristics of the struts, their behaviour and their location within the frame.

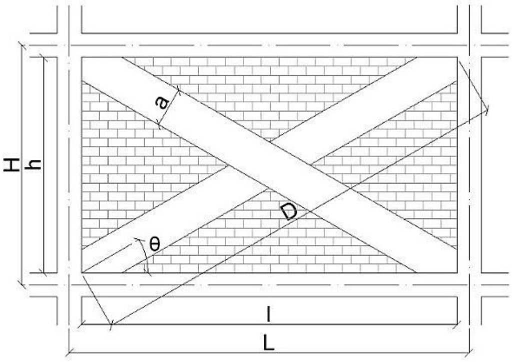

Figure 5. Geometrical parameters of the equivalent diagonal strut

The relative flexural stiffness frame-panel with E_c concrete Young's module, E_m masonry Young's module, I_{col} moment of inertia of the column and t thickness of the panel [52]:

$$\lambda_1 H = H \sqrt[4]{\frac{E_m t \sin(2\theta)}{4 E_c I_{col} h}} \tag{1}$$

Width of the equivalent strut is function of the previous value with the relation [53]:

$$a = 0.175 D (\lambda_1 H)^{-0.4} \tag{2}$$

If the panel presents openings, a reduction factor should be applied:

$$R_1 = 0.6 \left(\frac{A_{openings}}{A_{panel}} \right)^2 - 1.6 \left(\frac{A_{openings}}{A_{panel}} \right) + 1 \tag{3}$$

Anyway if the area of the opening is not minor of 60% of the area of the panel the effect of the infill can be ignored, and $R_1 = 0$.

For the purpose of a finite element model it is necessary also to define an equivalent diagonal that is connected to the beam at a distance l_{column} from the frame joint (Figure 6).

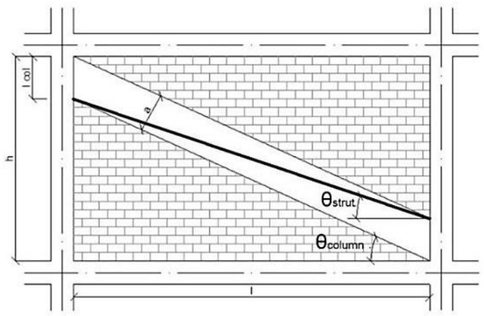

Figure 6. Equivalent diagonal strut for full and partial infill

$$l_{column} = \frac{a}{cos\theta_{column}} \tag{4}$$

$$tan\theta_{column} = \frac{h - \frac{a}{cos\theta_{column}}}{l} \tag{5}$$

The strength of the strut is determined calculating the required loads to reach the crushing strength R_{cr} and the shear strength R_{sh} of the panel and evaluating the component of those loads in the direction of the equivalent diagonal. The minimum value thus obtained represents the load connected to the compressive strength of the equivalent strut, R_{strut} , and it will be used to define the properties of the plastic hinge in the final element software.

$$R_{strut} = min\left\{ \frac{R_{cr}, R_{sh}}{cos\theta_{strut}} \right\} \tag{6}$$

$$tan\theta_{strut} = \frac{h - 2 l_{column}}{l} \tag{7}$$

$$R_{cr} = a_{red} t f'_m \tag{8}$$

$$R_{sh} = A_n f'_v R_1 R_2 \tag{9}$$

f'_m masonry compressive strength
f'_v masonry shear strength
A_n net area of the transversal section of the panel.

To determine the position of the plastic hinges it is necessary to define another relation:

$$l_{beam} = \frac{a}{sin\theta_{beam}} \tag{10}$$

$$tan\theta_{column} = \frac{h}{l - \frac{a}{sin\theta_{beam}}} \tag{11}$$

Rigid offset are added to avoid the excessive flexibility of the numerical model.

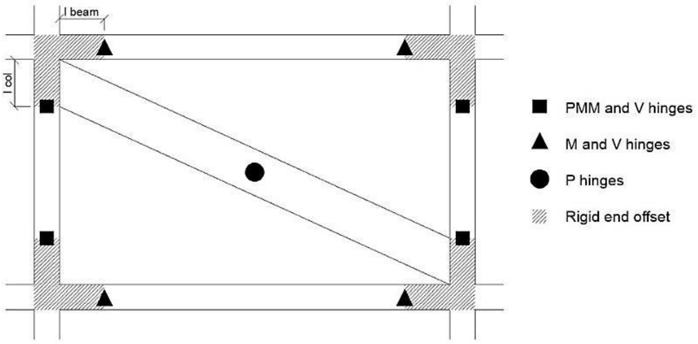

Figure 7. Location of plastic hinges and rigid end offsets

For the relation force-displacement of the equivalent strut Panagiotakos and Fardis's model [54] is used with a multilinear curve: in compression the curve is composed by four segments, which respectively correspond to the pre-cracking shear behaviour of the panels, to the post-cracking hardening branch after the detachment from the edges, to the instable state after the maximum strength, and to the ultimate state of the panel after the complete damage with a constant residual strength.

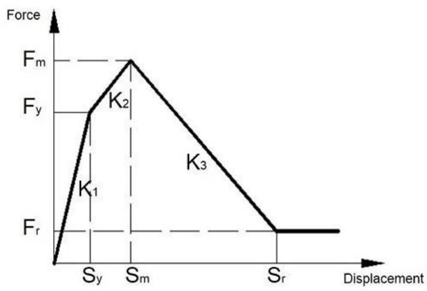

Figure 8. Panagiotakos and Fardis's force-displacement relation

Where the initial shear stiffness of the un-cracked panel is equal to:

$$K_1 = \frac{G_m t l}{h} \tag{12}$$

The cracking force is:

$$F_y = \tau_{cr} t l \tag{13}$$

The displacement relative to the cracking load is:

$$S_y = \frac{F_y}{K_1} \tag{14}$$

The axial stiffness of the equivalent strut is:

$$K_2 = \frac{E_m t a}{d} \tag{15}$$

The ultimate force is:

$$F_m = 1.3F_y \tag{16}$$

The displacement relative to ultimate force is:

$$S_m = S_y + \frac{F_m - F_y}{K_2} \tag{17}$$

The post-ultimate falling branch stiffness is:

$$0.005K_1 \leq K_3 \leq 0.1K_1 \tag{18}$$

The residual post cracking force is:

$$F_r = 0.1F_y \tag{19}$$

The ultimate displacement relative to the residual force is:

$$S_r = S_m + \frac{F_m - F_r}{K_3} \tag{20}$$

h, l, t, d	height, length, thickness and diagonal of the infill panel
a	width of the strut
τ_{cr}	cracking stress as measured in a diagonal compression test of the masonry

In the finite element software SAP2000 the infill panel are described as "frames" with a pure compressive behaviour and an axial plastic hinge located in the middle section of the diagonal. The force-displacement relation differs from the Panagiotakos and Fardis's one just for the instable falling branch, described as a constant branch in order to improve the numerical stability of the program; this choice does not influence the result of pushover analyses.

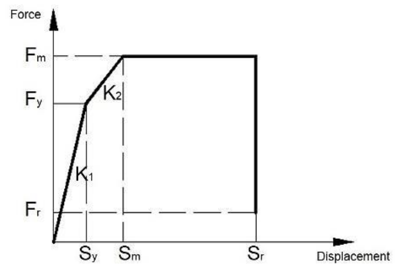

Figure 9. Force-displacement relation modelled in SAP2000

$$S_r = 20\, S_m \tag{21}$$

The software SAP2000 assumes for the "hinges properties" a rigid plastic behaviour with the definition by the user of the only the plastic range; the elastic response is indeed evaluated automatically in relation to the mechanical properties of the material and the geometrical characteristics of the elements. To assign the initial stiffness to the strut is then necessary to increment the section of the strut of the parameter K_1/K_2.

The building taken as case study is part of a social housing complex built in 1957 in Brescia (Italy) in the district of San Bartolomeo, in the northern part of the city.

The area, which at the time of construction was located in the urban periphery, is now part of the North District of Brescia and it is included in an area of low seismic hazard, with the possibility of moderate quakes.

The building is almost symmetrical in both directions, with plan dimensions of 10 meters per 40 meters and four floors, 3.1 meters high over a ground floor of 1 meter for a total elevation of 13.4 meters. The concrete frame counts irregular spans and a number of different sections for the columns (Figure 10).

In Table 1, the main characteristics of the building are listed, namely geometrical features of the structural elements and mechanical proprieties of the structural materials.

Figure 10. A building type A in the district of San Bartolomeo
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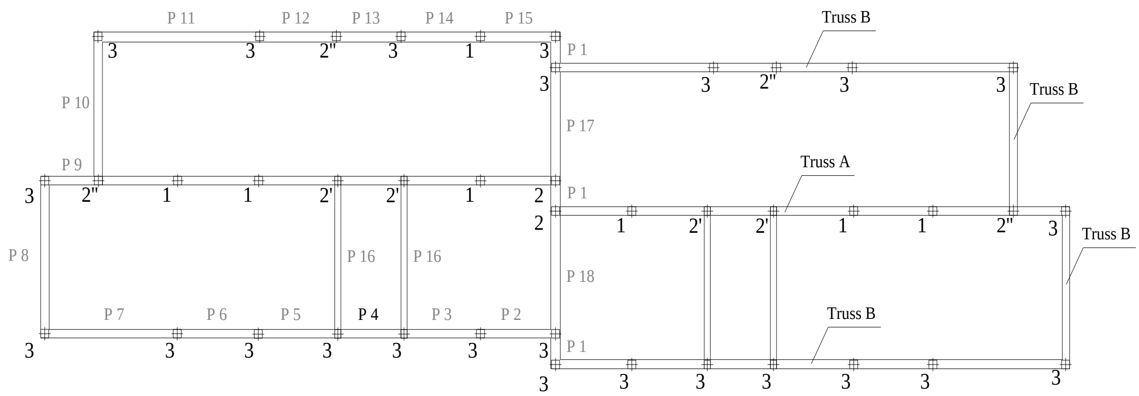
Table 1. Geometrical and mechanical characteristics of structural elements

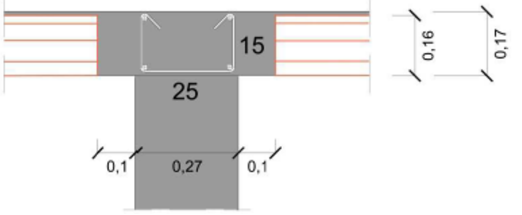


Materials properties
Masonry bricks "Trieste" type
Mass per unit value, 1.2 KN/m^3
Modulus of elasticity, E 5225000 KN/m^2
Shear modulus, G 2090000 KN/m^2
Poisson's ratio, 0.2
Specified compressive strenght, f'm 4000 KN/m^2
Concrete
Mass per unit value, 2.55 KN/m^3
Modulus of elasticity, E 31476000 KN/m^2
Shear modulus, G 13115000 KN/m^2
Poisson's ratio, 0.2
Specified compressive strenght, f'c 25000 KN/m^2
Rebar Aq50
Mass per unit value, 7.85 KN/m^3
Modulus of elasticity, E 199900000 KN/m^2
Shear modulus, G 76903069 KN/m^2
Poisson's ratio, 0.3
Minimum yield stress, Fy 270000 KN/m^2

Manimum tensile stress, Fu 500000 KN/m^2

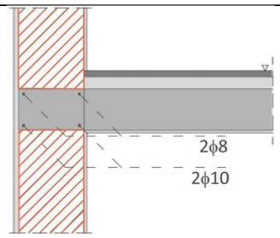
Trusses

Truss type A



Stirrups Ø5/25 cm (Ø5/15 at the joint between truss and column).

Truss type B



Stirrups Ø5/50-60 cm.

Columns

Column type 1	**Section (cm)**	**Reinforcement**
Floor 1	27x25	2Ø12+2Ø14
Floor 2	25x25	3Ø12+1Ø14
Floor 3	25x25	2Ø12+2Ø10
Floor 4	20x20	4Ø10
Stirrups		Ø5/15 cm
Column type 2	**Section (cm)**	**Reinforcement**
Floor 1	25x25	4Ø10
Floor 2	25x25	4Ø10
Floor 3	25x25	2Ø10+2Ø18
Floor 4	20x20	4Ø8
Stirrups		Ø5/15 cm
Column type 2’	**Section (cm)**	**Reinforcement**
Floor 1	25x25	2Ø12+2Ø10
Floor 2	25x25	4Ø10
Floor 3	25x25	4Ø10
Floor 4	20x20	2Ø10+2Ø8
Stirrups		Ø5/15 cm
Column type 2’’	**Section (cm)**	**Reinforcement**
Floor 1	25x25	4Ø10
Floor 2	25x25	4Ø10
Floor 3	25x25	2Ø10+2Ø8
Floor 4	20x20	4Ø8
Stirrups		Ø5/15 cm
Column type 3	**Section (cm)**	**Reinforcement**
Floor 1	18x18	2Ø12+2Ø10
Floor 2	18x18	4Ø10
Floor 3	18x18	4Ø10
Floor 4	18x18	4Ø10
Stirrups		Ø5/20 cm

Panels

	H (cm)	**h (cm)**	**l (cm)**	**t (cm)**		**H (cm)**	**h (cm)**	**l (cm)**	**t (cm)**
Panel 1					**Panel 10**				
Floor 1	310	293	75	27	Floor 1	310	293	435	27
Floor 2	310	293	82	27	Floor 2	310	293	438,5	27
Floor 3	310	293	82	27	Floor 3	310	293	438,5	27
Floor 4	310	293	82	27	Floor 4	310	293	438,5	27
Panel 2					**Panel 11**				
Floor 1	310	293	271,5	27	Floor 1	310	293	583	27
Floor 2	310	293	271,5	27	Floor 2	310	293	583	27
Floor 3	310	293	271,5	27	Floor 3	310	293	583	27
Floor 4	310	293	271,5	27	Floor 4	310	293	583	27
Panel 3					**Panel 12**				
Floor 1	310	293	277	27	Floor 1	310	293	301,5	27
Floor 2	310	293	277	27	Floor 2	310	293	301,5	27
Floor 3	310	293	277	27	Floor 3	310	293	301,5	27
Floor 4	310	293	277	27	Floor 4	310	293	301,5	27
Panel 4					**Panel 13**				
Floor 1	310	293	202	27	Floor 1	310	293	198,5	27
Floor 2	310	293	202	27	Floor 2	310	293	198,5	27
Floor 3	310	293	202	27	Floor 3	310	293	198,5	27
Floor 4	310	293	202	27	Floor 4	310	293	198,5	27
Panel 5					**Panel 14**				
Floor 1	310	293	305	27	Floor 1	310	293	286	27
Floor 2	310	293	305	27	Floor 2	310	293	286	27
Floor 3	310	293	305	27	Floor 3	310	293	286	27
Floor 4	310	293	305	27	Floor 4	310	293	286	27
Panel 6					**Panel 15**				
Floor 1	310	293	286	27	Floor 1	310	293	280,5	27
Floor 2	310	293	286	27	Floor 2	310	293	280,5	27
Floor 3	310	293	286	27	Floor 3	310	293	280,5	27
Floor 4	310	293	286	27	Floor 4	310	293	280,5	27

Panel 7					**Panel 16**				
Floor 1	310	293	497	27	Floor 1	310	293	464	27
Floor 2	310	293	497	27	Floor 2	310	293	465	27
Floor 3	310	293	497	27	Floor 3	310	293	465	27
Floor 4	310	293	497	27	Floor 4	310	293	465	27
Panel 8					**Panel 17**				
Floor 1	310	293	465	27	Floor 1	310	293	365	27
Floor 2	310	293	472	27	Floor 2	310	293	368,5	27
Floor 3	310	293	472	27	Floor 3	310	293	368,5	27
Floor 4	310	293	472	27	Floor 4	310	293	368,5	27
Panel 9					**Panel 18**				
Floor 1	310	293	182	27	Floor 1	310	293	335	27
Floor 2	310	293	182	27	Floor 2	310	293	338,5	27
Floor 3	310	293	182	27	Floor 3	310	293	338,5	27
Floor 4	310	293	182	27	Floor 4	310	293	338,5	27

At first, the seismic behaviour of the existing building was evaluated through nonlinear analyses and consequently a “building exoskeleton” with SMADs at the different floor levels was added.

The pushover analysis showed the capacity of the buildings at the different performance levels defined by the Italian code and the FEMA 356, applying horizontal loads for two orthogonal directions, for two load distributions, for positive or negative eccentricity, with eight combinations in total. The model required introduction of different groups of hinges in relation to the collapse modes for the columns combined compressive and bending failure and shear failure for the beams, and bending failure and shear failure for the panel, described with axial hinges.

The time history analysis assessed the interstory drift of a control point in relation to the Italian code using seven spectrum compatible accelerograms generated for the city of Brescia with the software SIMQKE for three of the four performance levels, namely operational (O), immediate occupancy (IO) and life safety (LS).

Pushover analyses underlined the necessity of an intervention (Figure 11, 12 and 13) that was realized verifying three types of SMADs with different level of initial precompression.

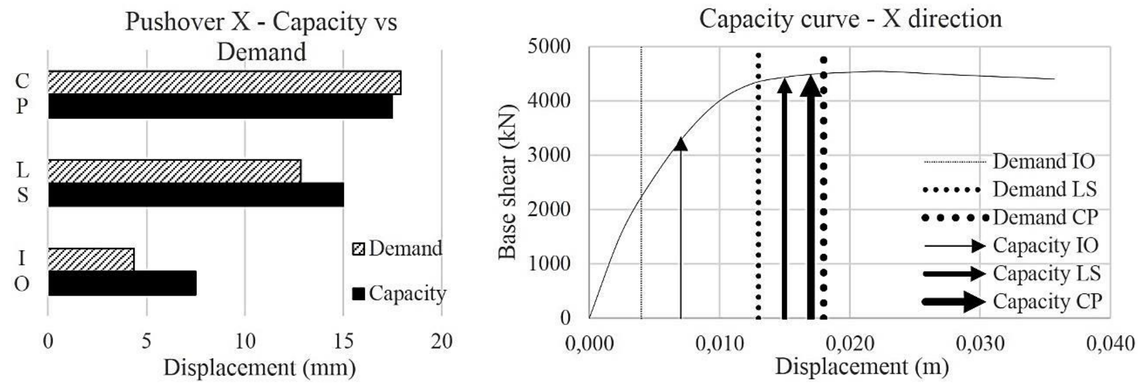


Figure 11. Results of a push over analysis

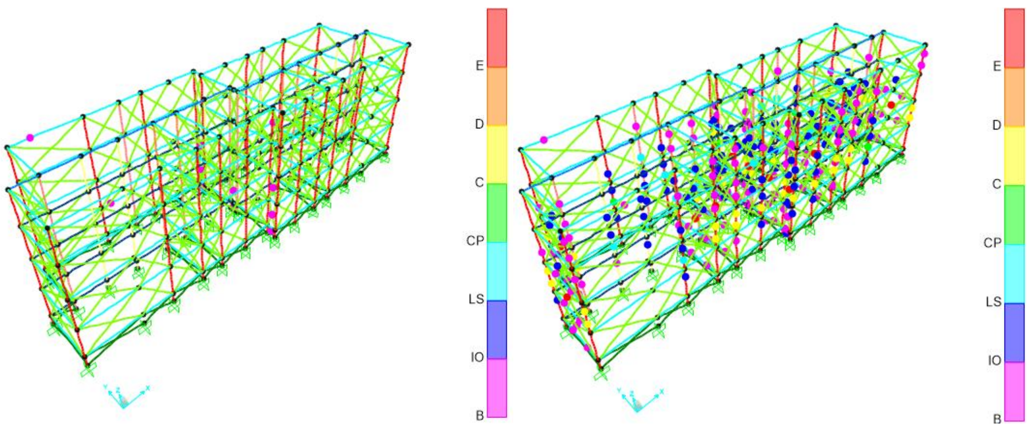


Figure 12. Pushover analysis applied on the existing building. On the left step 0, on the right last step

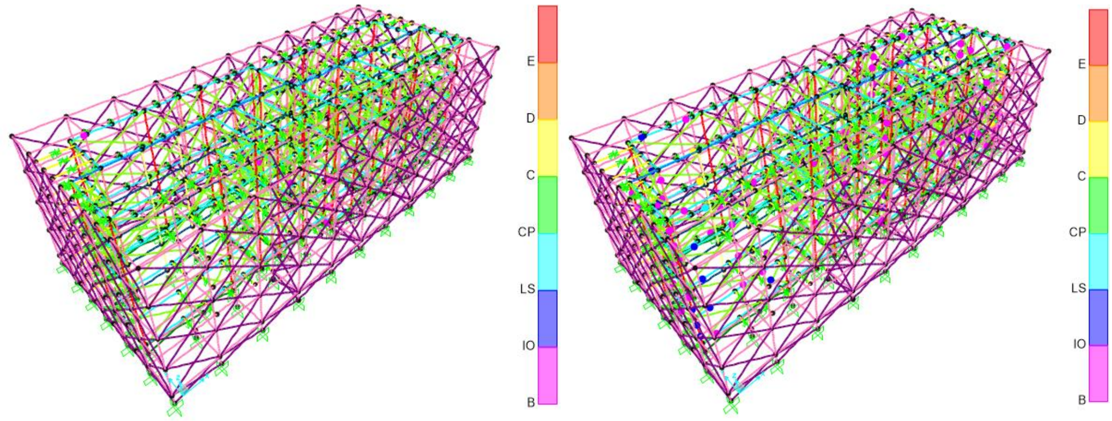


Figure 13. Pushover analysis applied on the building equipped with the "adaptive exoskeleton", SMAD type 05_10. On the left step 0, on the right last step

The time history analyses verified the interstory drift in relation to the limits imposed by the regulations integrated to achieve a clearer interpretation of the in-plane behaviour of the single panels, with the introduction of different performance limits and their relative definitions [55]:

- Operational level is verified when no panel reaches an interstory drift of 0.2%;
- Immediate occupancy level is verified when no panel reaches an interstory drift of 0.3%;
- Life safety level is verified when no panel reaches an interstory drift of 1%.

To evaluate the necessity of the procedure the limits were at first verified for the interstory drifts of the control points, coincident with the centre of masses of each floor, as in figure 14. In figure 15 the behaviour of the single panels before and after the intervention with the three typologies of SMADs are evaluated.

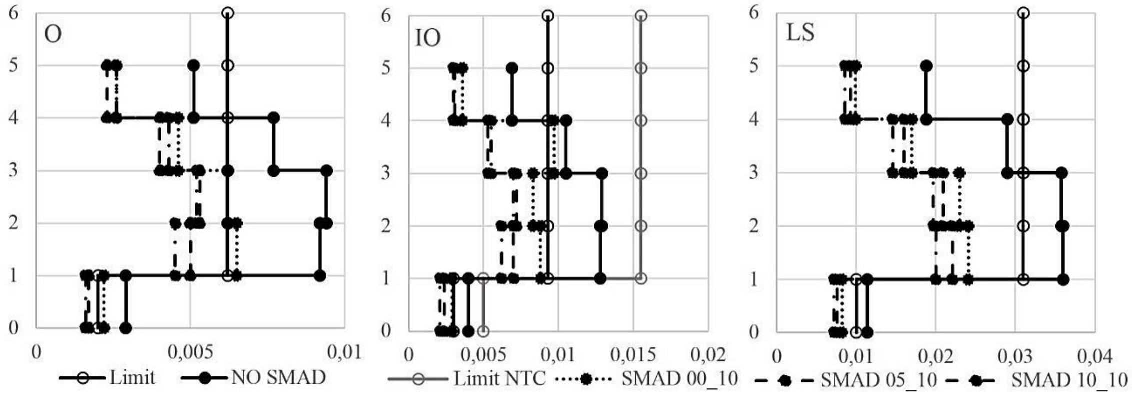


Figure 14. Time history analyses for the control point.

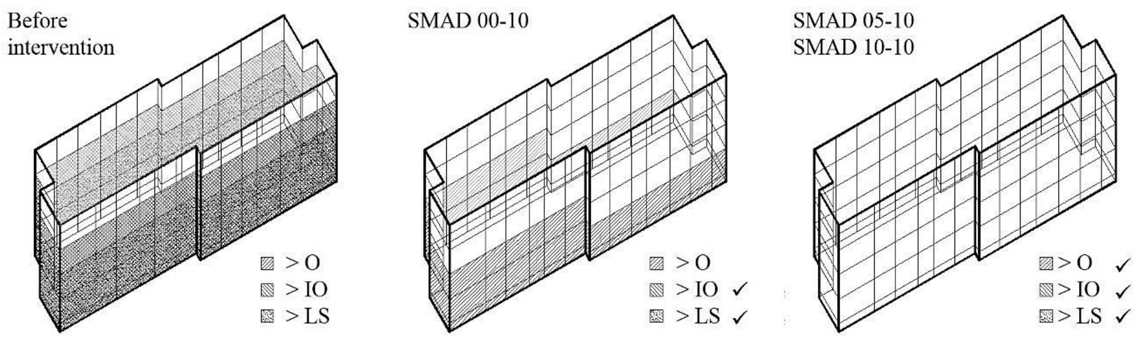


Figure 15. Time history analyses for the in-plane behaviour of the panels.

3.4. Economic Feasibility

Shape memory alloys showed a good potential for seismic dissipation in civil structures but the high cost per unit weight requires some considerations, in order to assess their practical feasibility and economic convenience [56].

Some researchers argue that the size of civil constructions and the high loads they are subjected to would require a large amount of material in comparison with other fields where SMA are already widely used such as automotive engineering and medical applications. Nevertheless, other studies demonstrated that also small amount of shape memory alloys, strategically located within a structure, can achieve considerable effects in the regulation of seismic behavior of civil constructions [57]. Additionally the price of shape memory alloys decreased considerably in the last decades: less than US$111 per kilogram today against the US$1100 per kilogram of the 1996 [58]. Despite that the price is still considerably higher than for traditional dissipation technologies.

The high cost of SMA sections is strongly connected with the complex production process [59; 60], requiring the improvement of the manufacturing techniques. At the same time a decrease in cost could be also achieved thanks to an increased demand for the material [61] so the promotion of a wide spread campaign of seismic retrofit based on SMADs could have some influence in economic convenience of the new technology.

Additionally to the previous considerations, Bruno and Valente [62] and Dolce and Marnetto [63] evaluated the costs of the SMADs in a full-scale construction in comparison with other already widely applied technologies. The study calculated the cost of SMA to be around 0.7% of the overall cost of the construction, while the cost of the entire seismic device is around 3.5%. These values are comparable with the other technologies and, in particular, in a steel bracing system for framed structures the cost of SMA resulted irrelevant with respect to the cost of the full device.

Moreover, SMA-based devices do not require additional expenses in terms of maintenance or replacement: they have high corrosion resistance and fatigue resistance, being able to recover their initial shape also after many loading cycle because of their superelasticy not undergoing plastic, unrecoverable deformations, and therefore not requiring replacements after a seismic event.

From the previous considerations, it appears that the use of SMA-based passive control systems can provide good overall performance, under some aspects better of the current technologies, while at the same time involving reasonable costs.

3.5. Energy Retrofit

At least one third of the housing stock is represented by building dated after the Second World War, characterized by a mix of construction techniques and typologies. All these buildings have instead in common the poor energy performances, due to the lacking or inefficient insulation [64].

The performance upgrading should ideally realized using minimum non-renewable energy, while providing comfort and efficiency at lower operating costs [65].

These interventions, other than allowing energy savings are economically and socially relevant in the long-term. Anyway, every building is different in terms of condition, location, materials, characteristics, etc. creating a complex scenario to interpret and evaluate so the first step is to recognize in a common building, which is the most influential elements in terms of seismic performances.

The envelope is indeed the liminal space between inside and outside, thus regulating the relationship between the building and the environment and it has therefore a leading role in defining new characteristics, performances but also the appearance of a construction [66].

The energy consumption for heating and cooling of buildings is directly related to heat losses through building envelope components, ventilation and air infiltration and inversely related to heat gains in the building through solar radiation, all parameters that depend on the design quality of the envelope of the building [67].

The “adaptive exoskeleton” is an effective intervention to strongly modify the energy performances of the building because it acts as a second shell, going far beyond the simple provision of an additional insulation layer. It can contain new service demands and technological innovations, benefiting from the use of renewable energy sources.

On the other hand, high reduction potential of heat loss is strongly dependent on the realization of an integral “adaptive exoskeleton” to avoid thermal bridging and bypass. In this sense, the design approach is still strongly connected with the urban conditions and the proximity with other constructions showing some limits.

Nevertheless, the possibility of customization of the different components and in general the construction process open a wide field of application in different climatic and geographic conditions, maintaining its attractiveness for future implementation of the idea (Figure 16).

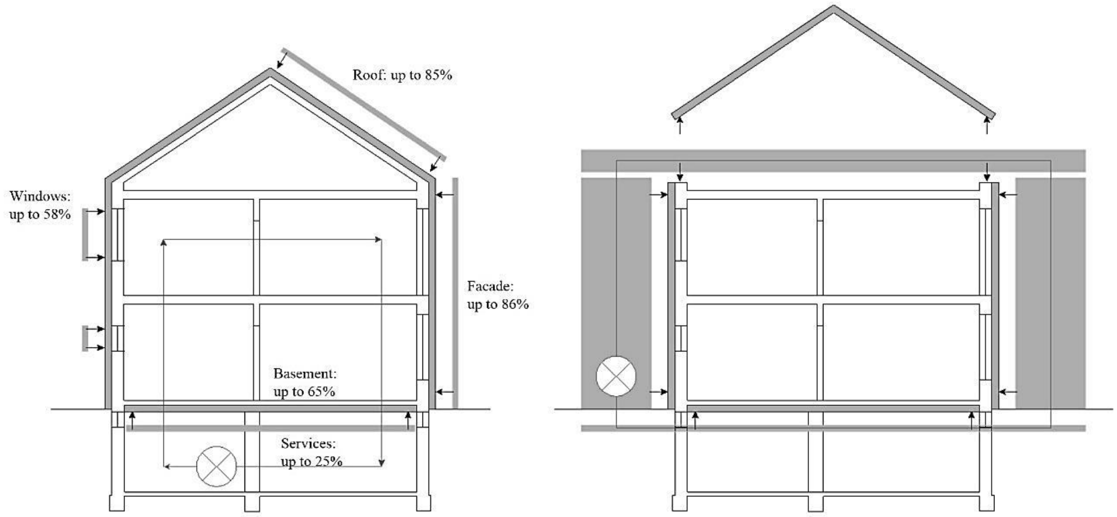


Figure 16. Reduction potential of heat loss for traditional retrofit on the left and with the exoskeleton on the right

4. Conclusions

This paper presents an innovative design, aiming at a biomimicry approach, for the integrate retrofit of social housing heritage.

The study of the state of the art revealed the existence of a number of interventions for social housing buildings focusing on the improvement of the energy performances and of the architectural quality of constructions. On the other hand, few studies experimented the possibility to merge these applications with seismic retrofit practices, missing the chance to achieve a full-integrated and multi-purpose intervention with significant economic convenience.

The presented proposal wants to fill this gap exploiting simple but effective structural design and the potentiality of the new smart materials for the passive dissipation of seismic loads. The apparent simplicity of the scheme aims at widespread applications, on national and regional levels, at the same time being able to provide variety and diversification in order to adapt to the different geographical, territorial and site contexts.

When the exoskeleton can develop in three-dimensions, new spaces and connections can be located, allowing the building to adapt progressively to the changing needs of the inhabitants.

The provision of the different functions and services can be cost oriented and the construction process can be industrialized, to provide and effective and economic solution at the same time giving the right amount of vibrancy and variety to the residential housing stock.

A multi-purpose scheme of intervention is necessary and it has as the focal point the realization of a seismic retrofit plan in order to reduce the vulnerability of the building stock.

The optimization of the design and of the location of the devices is a fundamental part of the retrofit design. In the presented study the devices are distributed on every floor level with a symmetrical pattern in both directions and the SMADs present full re-centring and good energy dissipation capabilities. These characteristics are achieved with two groups of Nitinol wire loops, which are mounted on two concentric tubes for a pure tensile behavior [68].

By changing the number of the loops, the lengths and the applied pre-tension of the two groups of SMA elements, different performance and dissipation levels could be reached, achieving a better optimization of the structural design.

Although some limit in application the design proposal appears promising for future applications and developments, concerning principally a careful design of the energy performances of upgraded buildings realized with this technique.

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