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Combining seismic retrofit with energy refurbishment for the sustainable renovation of RC buildings: a proof of concept

By

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In this paper, an integrated approach targeting sustainability, safety, and resilience is envisioned for the renovation of the post-World War II RC buildings clustered in urban outskirts. The solution stems as an enhancement of the widespread camouflage practice, which targets energy efficiency and architectural restyling by complementing the building with a technological double skin, self-supported on an independent exoskeleton. Based on this integrated approach, the exoskeleton can be further engineered to also enable structural safety and resilience. Life cycle thinking is addressed to re-conceive traditional structural design approaches, guaranteeing safety, while minimizing costs and environmental impacts over the building life cycle. Accurate selection of materials and dry technologies enables adaptability, reparability and maintenance, and total recyclability/reuse at end-of-life. The intervention is carried out from outside, avoiding relocation of the inhabitants and possible building downtime. The paper introduces a possible framework for engineers, technologists, and architects to design new holistic renovation interventions, for which innovative solution sets are required. Possible structural techniques to be coupled with energy refurbishment are proposed. As a proof of concept, the envisaged holistic renovation strategy is applied to a reference building, and benefits entailed in combining structural safety measures within an integrated intervention are commented.

Keywords: Sustainable building renovation, seismic and energy refurbishment, modern RC buildings, engineered exoskeletons, life cycle thinking, building retrofit from outside, enhancement of camouflage practice

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1. Introduction

The growing attention to sustainability has increased the awareness of the relevant environmental impact of the existing building stock, which is liable for 36% of the total energy consumption and CO_2 emissions throughout its life cycle, for about 50% of the raw materials depletion, and for 35% of the total waste generated in Europe (Marini et al., 2014). The need of renovation is therefore acknowledged as a priority to foster an effective transition toward a low carbon and eco-efficient society and to reach the European targets in terms of greenhouse gas (GHG) emissions.

In recent years, significant incentives have been granted for the improvement of energy efficiency, encouraging the upgrade of the envelopes and the use of renewable energy sources and eco-friendly materials. However, it is quite rarely considered that half of the existing building stock has exhausted its current nominal structural service life (50 years), often exhibits substantial structural problems and material decay. Furthermore, these buildings may be inherently vulnerable to seismic actions, given that rarely the design accounted for seismic actions and appropriate anti-seismic detailing at the time of construction. Sole energy upgrade may therefore leave these building dangerously unsafe.

High vulnerability of European constructions is particularly critical given that the updated seismic zonation has increased and extended the hazard level over the whole continent, making the seismic risk mitigation a priority to thrive resilience of European communities. The relevance of such vulnerability has been repeatedly proven by past earthquakes, resulting in substantial losses and casualties, which are unbearable from a social, economic, and environmental point of view. Reconstruction costs provide further evidence of the significance of the problem: for instance, Italy has been spending 3600 M€ per year for post-earthquake reconstruction since the Belice earthquake in 1968, excluding the 2016 earthquakes in Central Italy. Finally, a recent study has emphasized the relevance of the seismic vulnerability of buildings also under an environmental point of view, showing the impact associated to the seismic risk in terms of emissions related to the possible need of major repairs and reconstruction after an earthquake (Belleri & Marini, 2016). Impacts were shown to be even more critical when extended at district level, where the seismic risk affecting entire districts may impair the effectiveness of extensive energy saving measures.

Given these premises, the absolute need arises to broaden the concept of sustainability, commonly related to the sole environmental issues, to also include structural safety and resilience. In fact, question arises whether sustainability be really pursuit if energy saving measures are lost after an earthquake and, most importantly, if preservation of human life is not guaranteed.

In this paper, an extended concept of building renovation is introduced targeting environmental, social, and economic sustainability by combining structural safety measures in the integrated renovation process. In particular, such an approach can be described as holistic, contemporarily solving all building deficiencies (related to structure, energy efficiency, living discomfort) within a unique refurbishment solution; it is carried out from the outside, therefore avoiding building downtime and inhabitant relocation; and it targets eco-efficiency by reducing the environmental impact of the renovation system from the construction to the end-of-use.

Although this concept could be extended to the whole obsolete building stock, this paper focuses on the post-World War II reinforced concrete (RC) structures, representing about 50% of the European building stock (Marini et al. 2014). These constructions, often clustered in degraded urban suburbs, are typically multi-storey frame structures well separated from the neighbouring buildings, with poor and anonymous architectural features, characterized by extremely high operating energy and living discomfort, and with high seismic-vulnerability.

The paper, while introducing a new approach for the integrated renovation of existing buildings, emphasizes the importance of stimulating discussions among peer, within and across the topics, and of creating teams with different skills and expertise such as energy technologists, structural engineers, and architects. The awareness of the structural obsolescence is an important aspect that must be considered as a driving component in the conceptual design of the holistic building renovation. The paper describes the concept of this new renovation approach and its benefits, particularly referring to the structural aspects and provides an overview of the possible structural techniques that may be coupled to the energy refurbishment to increase the seismic resilience of existing buildings. Each solution is described under a conceptual – and not technological – point of view in order to emphasize both the potentialities and the challenges of the holistic approach. Finally, the concept is applied to a reference building, for which a possible holistic retrofit intervention is preliminary conceived. Improvement of the energy and seismic behaviour of the building is briefly assessed and commented.

2. Renovation practices: from traditional uncoupled interventions toward a more inclusive, holistic approach

European post-WWII RC structures were mainly built to quickly meet the pressing housing demand of those times, often in the absence of any planning and lacking the main seismic regulations. Under a structural point of view, they are characterized by one-way RC frames, with poor structural details and masonry infills. Floors are usually made by one-way composite RC-masonry ribbed slabs, often lacking a RC overlay, and "pilotis" or ribbon windows are often present at the ground floor. All these features contribute to the high seismic vulnerability of these constructions, often bound to the onset of soft-story mechanisms or brittle failure of squat columns triggered by strong earthquakes. Seismic vulnerability is also affected by the frame–to–masonry infill interaction. Buildings having regular infills distribution and located in low seismicity zones may benefit from the presence of infills, which provide the seismic resistance by enforcing a confined masonry behaviour; whereas frame-infill interaction is often negative in highly seismic prone areas, when the infill presence entails a substantially high structural stiffness, with larger inertia forces applied to the structure that in turn may result in the collapse of the infill and in the early collapse of the frame (Dolsek & Fajfar 2008, Hak et al. 2012, Manfredi et al. 2012).

Regardless of the substantial deficiencies of post WWII buildings, demolition and reconstruction may only be occasionally actualized, but could not be extensively practiced because excessively impacting in terms of both raw material depletion and hazardous waste production (Eurostat 2013).

In Europe, renovation of existing RC buildings is typically approached by solving episodic and contingent problems exhibited by single buildings, either referring to specific energy, architectural, or structural deficiencies. They are often carried out in emergency situations, following a "non-integrated" approach, and disregarding both urban scale and context. Typical examples of the results of such a not-combined approach are shown in Figure 1. This non-integrated approach has failed for many reasons, as for instance: uncoupled interventions can be significantly more expensive than an integrated solution, and sole energy upgrade of vulnerable existing buildings may not guarantee long term protection of the human life and of the investment.

Focusing on structural retrofit, traditional approaches can be distinguished into "local" and "global". The "local approach" consists in retrofitting frame joints and members, through jacketing with high performance materials (Martinola et al. 2007, Beschi et al. 2015) or FRP wrappings (Antonopoulos & Triantafillou 2003, Di Ludovico et al. 2008). The intervention is usually quite expensive as it requires substantial demolition of the finishing, temporary relocation of the inhabitants and downtime of the building; such intervention is ineffective in the case of one-way frames or shallow beams, and its effectiveness may be jeopardized by operational difficulties during installation. The "global approach" consists in complementing the frame with a brand new seismic resisting system, by either adding shear walls, by strengthening the existing frame with bracings, or by jacketing selected infilled bays or RC walls not designed for seismic actions (Marini & Meda 2009). Despite being very effective from a structural point of view, such an approach may raise architectural and formal compatibility issues.

As regards the energy upgrading of buildings, one of the main refurbishment strategies involves the upgrade of the building envelope system. Traditional systems, which are usually carried out from outside, consist in the improvement of the thermal insulation of building facades and roof, the correction of thermal bridges, and the creation of solar greenhouses and double skins (Angi 2016, Marini et al. 2014).


a)

b)

c’) c’’) d)

Figure 1. Non-integrated approach: a) post-earthquake scenario of energy saving measures carried out disregarding structural vulnerabilities (retrieved from: ADNKronos); b) structural retrofit carried out disregarding architectural context (www.studiomapi.it). Example of partially integrated approaches: c’) and c’’) ante and post camouflage intervention of Tour Bois-Le-Prêtre, Paris by Druot, Lacaton & Vassal, 2012; d) detail of the self-supporting exoskeleton, independent of the existing structure (Angi 2016).

Few pioneering projects have been carried out in Europe to tackle the building stock renovation in an integrated way. Distinguished examples were carried out in France, Germany, Netherlands, Denmark, UK coupling energy upgrading, architectural restyling, and urban regeneration with either “camouflage interventions” (or double skin, Fig. 1c) or through “remodelage”. Such interventions usually consist in re-designing the building total volume through selected demolition and expansion works, often introducing a self-supported exoskeleton, separated from the existing structure (Masboungi 2005, Fig. 1d). Noteworthy, in none of these European cases structural issues were ever considered, except for the energy-seismic retrofit carried out in Japan by Takeuchi et al (2009), but for quite different environmental conditions. The feasibility of engineering the classical curtain walls to also sustain seismic actions is shown in Passoni (2016).

Starting from the important inheritance of the camouflage interventions, the scientific community is now offered the opportunity to further engineer the retrofit solutions in order to combine structural safety and resilience upgrade measures within an effective and integrated renovation process. Such holistic approach may foster new research topics, focusing on innovative renovation processes and new solution sets need to be designed and tested.

3. A concept for a holistic renovation approach targeting sustainability and resilience

In this paper, a **holistic** approach is envisioned for the renovation of post-WWII RC buildings fostering resilience, safety, and sustainability. This renovation approach targets the integrated solution of all building deficiencies and needs through a global intervention (Montuori et al. 2009, Angi 2016), and it stems as an enhancement of the camouflage interventions, in which the self-supporting exoskeleton is further engineered and designed to also enable structural safety and resilience. In the proposed solution the additional exoskeleton is equipped with all structural safety measures systems, besides implementing technological devices enabling the improvement of energy efficiency, architectural, and urban context quality.

By integrating structural retrofit in the renovation process, the solution entails important co-benefits (Fig. 2): (a) elongation of the building structural service life, which would be left unchanged by any intervention disregarding structural issues, such as the sole architectural and energy upgrading; (b) improvement of the seismic resilience at district level; (c) minimization of post-earthquake building downtime; (d) reduction of the environmental impact associated to seismic risk over the building life cycle; (e) possible addition of new stories, whose sale revenues might partially cover renovation costs; (f) long term protection of the investment, otherwise jeopardised by possible severe damages caused by either earthquakes or structural decay; (g) reduction of the total cost and payoff of the renovation also related to the improved building resilience; (h) advantage of a single construction site for both architectural, energy and structural renovation, with the added benefit that some of the components may serve multiple purposes, (i) wise investment of the tangible savings obtained with the energy efficiency improvement in the structural intervention.

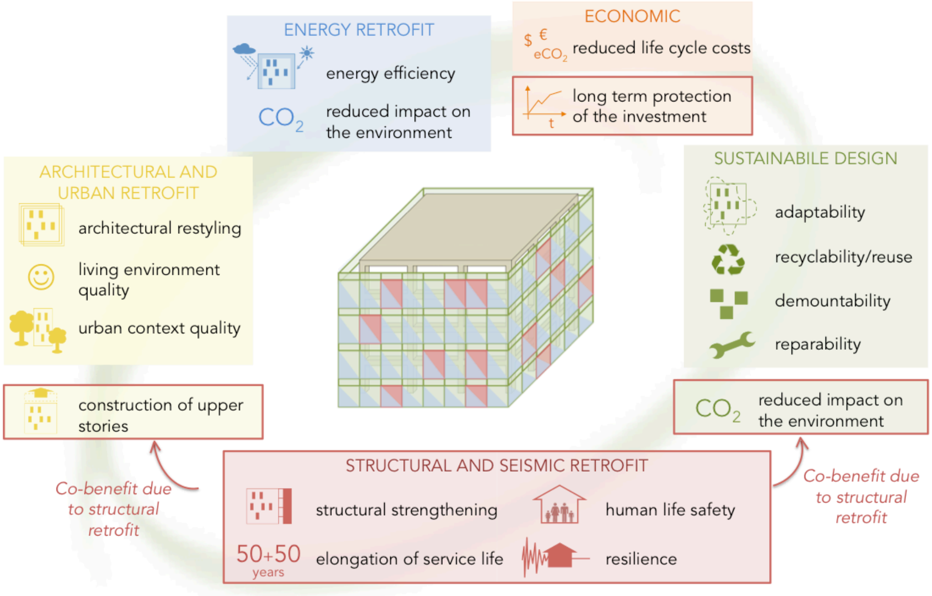


Figure 2. Main targets of the proposed holistic renovation strategy, fostering sustainability and resilience. Co-benefits obtained by integrating structural safety measures within a "traditional" camouflage intervention (see red boxes)

As mentioned, the proposed intervention is mainly envisioned as carried out **from outside the building**. This is a great challenge under both a social, structural, and architectural point of view. From a social point of view, the possible continuous usage of the building may both remove the well acknowledged barrier to the renovation process and reduce the costs associated to the relocation of the inhabitant and of the building functions (FEMA 398). As regards the anti-seismic function of the exoskeleton, operating from outside implies a major effort in the evaluation of the in-plane capacity of the existing floors, in the definition of possible innovative intrados, dry and lightweight diaphragms which may be required, as well as in the study of the connections between the additional structure and the existing building and in the possible strengthening or weakening of stiff elements such as staircase walls and infills is not trivial. Under an architectural point of view, depending on urban planning restrictions the exoskeleton may either adhere to or may be an enlargement of the existing building, thereby allowing the construction of additional living spaces, balconies, and new stories. This way the intervention fosters urban densification, and rises against urban sprawl and the following loss of open land as recommended by the European Roadmaps. Interestingly, when replicated at district level, the proposed solution foster the urban regeneration of the city outskirts, which become more pleasant to live in, more sustainable, resilient, and structurally safe.

Regarding the **eco-efficiency** of the intervention, unless demolition is mandatory, the solution is a sustainable alternative to the demolition and reconstruction practice; careful attention is paid since the design stage to minimize the use of raw materials and to reduce waste production (Fig. 3).

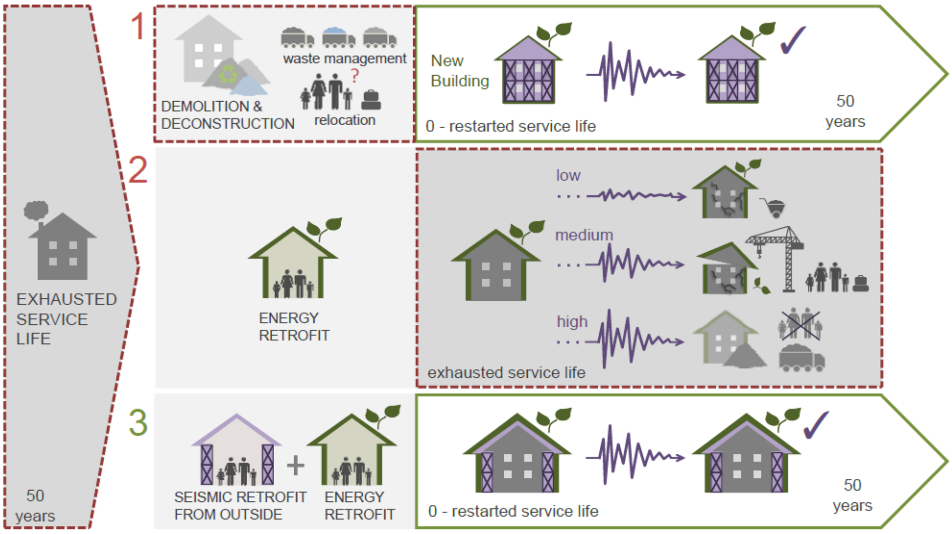


Figure 3. Major benefits and limitations of: 1) demolition and reconstruction, 2) energy measures only, 3) integrated renovation (adapted from Belleri & Marini, 2016).

In order to boost the eco-efficiency of the proposed integrated renovation practice, the common design approaches must be re-conceived. The concept of Life Cycle Thinking, usually applied to foster the sole environmental sustainability, is here applied also for safety and resilience, contemporarily targeting maximization of the performances and minimization of environmental impacts and costs throughout the building life cycle (Fig. 4). To this end, the effective involvement of different professionals should be envisioned to define the multidisciplinary targets of the intervention from the early stages of the design process.

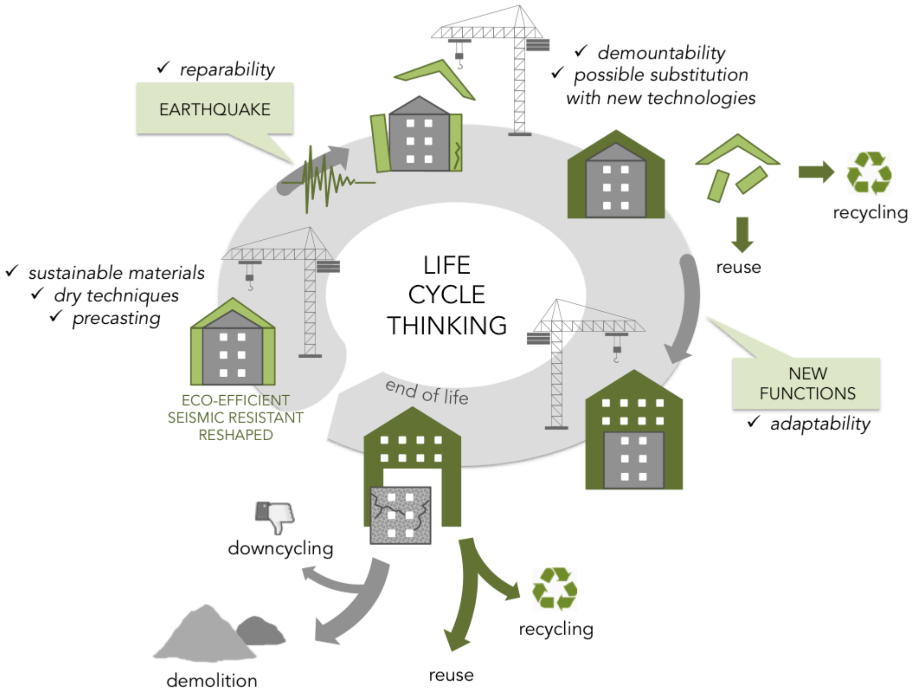


Figure 4. Life Cycle design for Sustainability and Resilience targets

Focusing on structural design within a Life Cycle Design approach, besides ensuring safety at serviceability and at ultimate limit states, mindful selection of materials and technologies becomes critical in ensuring effective minimization of environmental impact and cost over the life cycle. Materials and solution sets enabling easy maintenance, reparability after a seismic event, substitution and adaptability to possible future needs, should be preferred. Complete demountability, selective dismantling, and total recycling or reuse of components at the end of life becomes essential to increase sustainability, possibly targeting minimum cost, nearly-zero energy, and nearly-zero waste constructions.

4. An overview of possible structural solutions and their feasibility

Under a structural point of view, carrying out a seismic upgrading intervention completely from outside and integrating the structural elements within an energy and architectural façade, also respecting urban planning restrictions, requires a remarkable design effort. Traditional anti-seismic interventions must be completely re-thought or adapted to fulfil the new requirements, and new, ad-hoc solutions should be studied. In addition, only environmental-friendly materials and demountable dry techniques should be adopted to comply with the sustainability requirements.

In the following, an overview of some structural solutions that may be addressed in the design of the multi-purpose exoskeleton upgrading seismic resistance of buildings and energy efficiency are briefly outlined. This is intended as a tool and inspiration for structural engineers, energy technologists, and architects to envision new possible integrated renovation techniques. Obviously, this brief explanation does not exhaust the subject. The details of each solution need further development with the contribution of each professional, and each technology should be ad-hoc designed and adapted to the considered buildings.

Regarding the structural layout, the anti-seismic function of the engineered exoskeleton may be attained in two main ways (Fig.5): (i) by introducing shear walls or braced frames or (ii) by exploiting the whole external new envelope shell or box-structural behaviour.

In the shear wall solution, strength and stiffness, as well as seismic actions, are lumped into a few elements. Such elements must be encased in the exoskeleton, which in turn may become quite massive and resistant, and require new foundations (Fig. 5a). Both traditional steel braced frames or RC walls (Riva et al. 2010) and innovative rocking or hinged walls (Qu et al. 2012, Belleri et al. 2014, Gioiella et al. 2017) could be adopted. With this solution, energy efficiency upgrading is guaranteed by the finishing curtain walls or by the envelope attached to the exoskeleton. In this case, the two structure-energy systems work in parallel.

When the stiffness required to the additional structural system is too high to be obtained with walls of regular dimensions, shell solutions may be adopted. In the shell solution, the new façades are exploited to enforce a box-structural behaviour (Giuriani & Marini 2008, Giuriani et al. 2015), resulting in a substantial reduction of the size of each structural component and in a reduced foundation overload (Fig.5b). Given the lowered stress level, the energy efficiency upgrade and structural safety could be achieved through a dual-use of the same elements: for instance, the thermo-insulating envelope could be used also as an in-plane seismic resisting structure. When located in close proximity to the building, the new envelope becomes a structural-thermal coating. Within this category, diagrids (Labò et al. 2016; Labò et al. 2017), gridshells, and traditional curtain walls (Passoni 2016) can be re-engineered to behave like shell structures.

Both shell and shear walls must be conceived as fully demountable and conveniently supplemented with other components in order to guarantee sustainability. Dry solutions, standardised connections, as well as eco-compatible materials and recyclable devices should then be used.

When necessary, both shear walls and shell can be designed as dissipative elements. Shear walls can be conceived as either dissipative bracing systems (Fig.5c, Metelli 2013, Christopoulos & Filiatrault 2006), or hinged wall systems (Wada et al. 2009, Gioiella et al.2017), or connected to the existing RC frame through dissipative links (Xu et al. 1999, Trombetti & Silvestri 2007). The latter solution enables lumping damage into few sacrificial elements, protecting the main structure and the energy upgrade system. Sacrificial elements can be replaced after an earthquake, thereby lowering repair costs and shortening building downtime (Pampanin 2012). Among the more innovative and integrated solutions, dissipative shell structures could be considered (Fig.5d), where sub-components can be further engineered to dissipate energy either within the panels (Passoni 2016, Agha Beigi et al. 2014), or along the interfaces of adjoining elements (Preti et al. 2017), or along the interface of the new shell with its foundation (Labò et al. 2016; Labò et al. 2017). Regardless of the adopted solution, lumping the damage into replaceable elements triggers another challenge for the integrated intervention, given that the energy system must also be designed to accommodate possible localized displacements and to enable inspection, maintenance, and substitution of structural components.

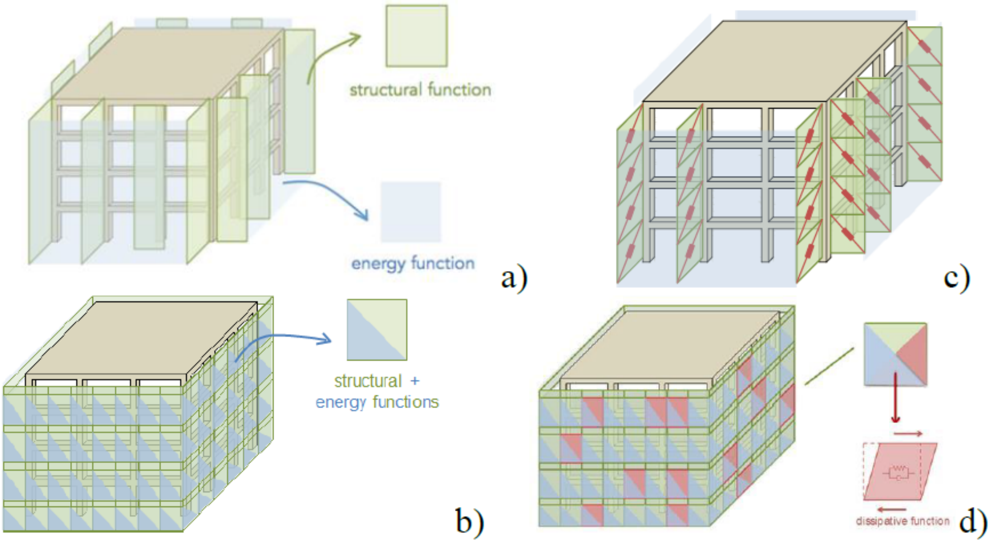


Figure 5. Retrofit solutions: a) non-dissipative or c) dissipative shear walls embedded in the external exoskeleton; b) non-dissipative shell structure with twofold use of the same encasing components, d) dissipative shell structure.

In order to further reduce the dimensions of the structure and to further boost adaptability and reparability, responsive solutions may also be adopted. Similarly to responsive façade systems or bio-inspired kinetic structures (Loonen 2015), which modify their behaviour for varying climatic conditions, both shear wall and shell solutions can be re-conceived to change their properties as a function of the earthquake intensity (Fig.6). Responsive systems can be designed as to avoid possible damage for low intensity earthquakes, while for higher seismic actions a change of the static scheme can be triggered to reduce the structural stiffness. As a result, the fundamental period can be lengthened, thereby reducing the seismic action on the building while increasing the displacement demand. Responsive structures can be conceived as either passive, if equipped with sacrificial elements that break or yield without requiring any supplied energy, or active, if actuators are implemented.

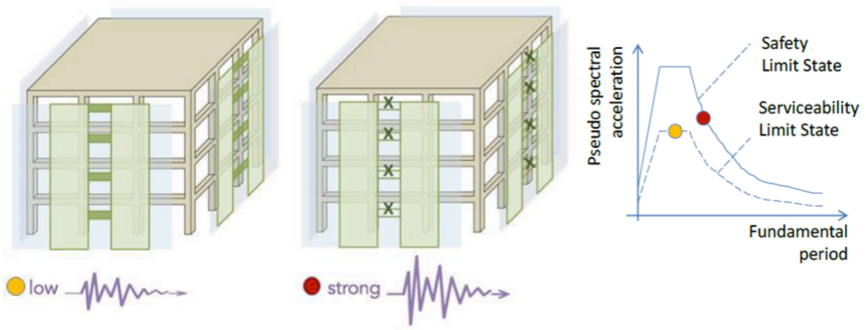


Figure 6. Schematic representation of responsive structures: dual-wall solutions with specifically designed coupled beams.

In order to choose among these solutions, some general consideration should be outlined about the feasibility of the intervention. As a first critical issue, the retrofit design mainly depends on the characteristics of the existing building, especially on its initial stiffness and possible structural irregularities. Usually, infills and stairwells make post WWII buildings particularly stiff, with a reduced displacement capacity. In this case, dissipative solutions may be often unviable since the collapse of the building may occur for very low displacements. For the same reason, in high-seismicity areas, resorting to non-dissipative retrofits might entail strong impacting of the new anti-seismic structures competing with the existing building stiffness. In these cases, responsive solutions may be a suitable solution.

Alternatively, preliminary interventions aimed at regularizing the structural response and at reducing the initial stiffness of the building can be undertaken, for example by disconnecting or downgrading the infills (Ireland et al. 2006, Mohammadi et al. 2011, Preti et al. 2015, INSYSME project 2016).

When extensive preliminary corrective measures are unviable and/or responsive solutions may not be applied, i.e. when there is no room for an exoskeleton, another structural solution may be adopted. The retrofitted building response can be controlled by either pursuing the structure base isolation (Fig.7a) or by enforcing a base isolation-like behaviour (Fig. 7b, Passoni 2016). The latter case is an innovative method that envisions the downgrade of the stiffer elements at the ground floor only, where local interventions increasing the ductility of the columns and additional dissipative bracings are introduced to counteract the induced soft storey mechanism. An example of dissipative bracing has been studied by Agha Beigi et al. (2014) for buildings presenting a soft storey structural layout.

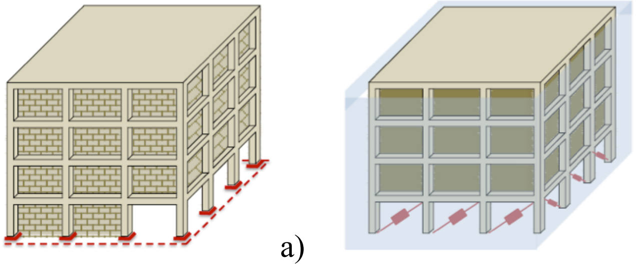


Figure 7. Schematic representation of a) base isolation and b) isolation-like intervention.

Finally, it is worth noting that the feasibility of all the outlined external solutions relies on the floor diaphragm action. Noteworthy, floor in-plane failure is rarely observed in the aftermath of an earthquake, but it may become an issue after the retrofit, especially with non-dissipative solutions, since larger seismic actions might be transferred across the floor as a result of increased stiffness. The need of strengthening existing floors to trigger in-plane diaphragm action may require internal works, thus missing the target to operate from outside the building, and may thereby hinder the whole renovation process.

The actual in-plane resistance of existing floors is the topic of an ongoing research. The preliminary numerical and experimental results (Feroldi 2014, Passoni 2016) showed that, in low to medium seismicity zones, the existing composite brick-RC slabs perform like in-plane rigid diaphragms by developing an arch-and-tie system within the thickness of the floor, which collects and transfers the seismic action to the seismic resisting walls. The main failure mechanisms governing the in-plane ultimate response of the beam and block floor systems were analysed, and the strength of the brick-to-RC joist interface was acknowledged as determining the floor capacity.

Based on the preliminary results of this research, existing floor strengthening may only be required at the upper levels of buildings located in high seismicity zones. When floor in-plane strengthening is needed, “dry solutions” such as intrados diaphragms made of steel truss work connected to the floor intrados, concealed at the sight with false ceilings, were proposed (Feroldi et al., 2013). As an alternative solution, new diaphragms can be assembled in the floors of the external gallery bridging the new shear walls; this solution minimizes disruptions to the inhabitants and meets the target to operate from the outside. In the latter case, connection of the external diaphragm to the existing frame can be guaranteed through post tensioned tendons and deep anchorages to transfer tensile actions, and studs to transfer shear forces or specific devices to be appositely designed. The same connections can be adopted to fix the existing building to the new seismic resisting walls at the floor level.

5. Preliminary assessment of the proposed concept: holistic renovation of a reference existing RC building

The proposed holistic retrofit approach is addressed for the possible renovation of a reference building representative of the considered post-WWII RC construction typology. A traditional energy and architectural double skin is proposed, but its structural exoskeleton is here modified to include and conceal steel shear walls. Like traditional camouflage interventions, the solution allows adding new living spaces, increasing the living comfort and the real estate value, and improves the global energy efficiency. At the same time, the renovation also improves the seismic performances of the building.

The building, built in 1972, lays in the suburb of Brescia (Northern Italy) and it is part of a larger residential complex of about ten buildings with similar features (Fig.8a,b).

Figure 8. a) Residential district in Brescia (Northern Italy), where the reference building is located; b) view of the southern façade of the case study building.

The construction has a 25.5m x 10m plan, three floors, and a basement. Its location in the lot and its distances from both the property lines and the neighbouring buildings represent the main urban planning constraints to reckon with when conceiving the new intervention. In this case, according to Italian regulation, the new exoskeleton may be designed as an enlargement of the existing building only on the southern side (Fig.8b), whereas the new multi-purpose exoskeleton and envelope must be in close proximity to the existing façades elsewhere, taking advantage of the sole additional 20 cm that can be derogated from the urban planning restriction when implementing energy saving measures.

A possible layout of the proposed holistic intervention is shown in Figure 9, in which the new structural system is integrated within the energy and architectural refurbishment. The energy refurbishment is obtained by adding a new glazed façade including solar greenhouses on the south part of the building. The maximum distance of the exoskeleton southern edge from the existing façade, corresponding to the "depth" of the additional living space created by the exoskeleton, is approximately equal to 1.6m (see also Fig. 10). Thermal insulation layers are added on the other sides. Windows are substituted, and a shading system is installed on the new façade to enable better control the solar gain. In order to increase the seismic resistance of the building, a shear wall solution is adopted, in which new walls (both in the transverse and longitudinal directions) are added and enclosed in the "depth" of the exoskeleton of the new southern façade.

Among the solutions discussed in the previous sections, the simplest techniques are here intentionally applied both in terms of energy and seismic upgrade. Aim of this example is to show that even two traditional techniques, frequently adopted in non-integrated renovation projects, may be even more effective when synergistically applied, by improving the overall energy, structural and functional performance, while entailing other relevant co-benefits such as those described in Section 3 (including the total cost reduction, the addition of living space, the protection of the investment, etc.) More advanced solution sets and innovative integrated techniques are being studied in an ongoing research.

The preliminary design of the structural intervention and of the energy refurbishment is briefly summarized in the following. References to the extensive discussion of the retrofit are provided at each section.

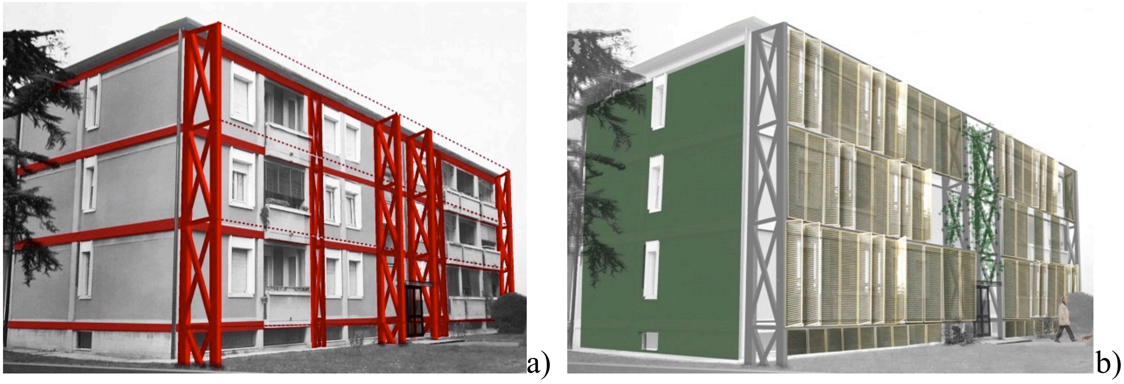


Figure 9. (a) View of the external anti-seismic structure which is integrated in the exoskeleton and partly concealed from the sight from the new casing on the Southern façade of the building; (b) example of a possible engineered double skin applied to the reference building; the outer coating is made of adjustable louvers hosting solar greenhouses and filter spaces for improving energy efficiency (the finishing layer is inspired by Sauerbruch & Hutton's architecture.)

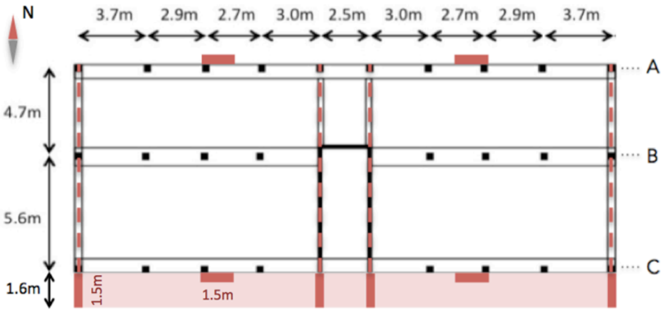
5.1 Seismic refurbishment

In the reference building, the gravity load resisting system is provided by three RC frames spanning in the longitudinal direction. On the southern side (Fig.8b), the longitudinal frame is characterized by short columns due to the presence of ribbon glazing in the basement. The frames are connected in the transverse direction through 20.5 cm one-way composite brick-RC ribbed floors, with a 25mm un-reinforced concrete overlay. Transverse side frames with two brick leaf infills (12+8 cm) close the building east and west ends.

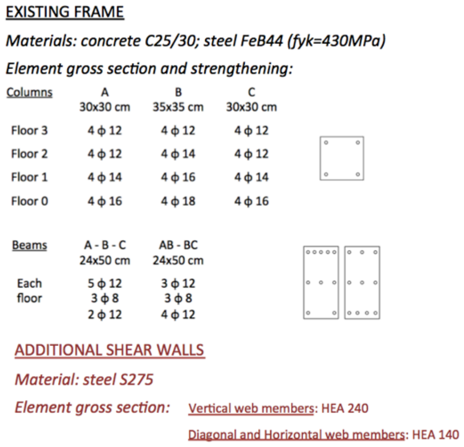
As for the structural analysis, the building finite element model is assembled with reference to both original specifications and construction documents. Geometry, materials, and reinforcement details of the structural elements of the existing frames are shown in Fig.10a,b. Columns and beams are modelled with lumped plasticity beam elements with non-linear hysteretic behaviour typical of RC elements; the rotational capacity of the plastic hinges is determined by means of sectional analysis (Fig.10c, NTC, 2008). The infill panels are modelled with equivalent diagonal compression-only struts (Decanini et al.1993, Fig.10d), and the floors are considered as in-plane rigid diaphragms due to their capability of developing an arch-and-tie system within the thickness of the floor (Section 4; Feroldi 2014, Passoni 2016). The columns are considered as fixed at the base, while the influence of the ground deformability at the base of the staircase walls is considered by introducing spring supports – calculated considering an equivalent modulus of subgrade reaction of the soil, $k=0.1N/mm^3$. The mesh adopted in the analyses is shown in Figure 11a (left).

3D nonlinear static analyses are carried out using the software MidasGen 2015 v.2.1 (MidasGen, 2015) to investigate the structural performances of the existing building. The capacity curves highlight a reduced displacement capacity of the structure, which is mainly associated with the early collapse of the staircase and infill walls in Y direction, with the following onset of a soft story failure mechanism and with the shear failure of the squat columns alongside the basement of the southern façade in both X and Y directions (Fig.11b). After the failure of the squat columns, the building is no longer structurally safe, even for the gravitational loads, and the capacity curve is only conventional (dotted part of the curve in the Y direction in Fig.11b).

As for the seismic vulnerability assessment, the seismic displacement demand in both directions was evaluated considering the Response Spectrum at the Life Safety Limit State (LSLS) according to the Italian Building Code (NTC, 2008), for the city of Brescia, site class C, and topography category 1. Figure 11b shows that the displacement demand is not satisfied for the existing building at the LSLS. Figure 11c shows the interstorey drift localization at the ground level at the LSLS, following the onset of the squat column shear failure mechanism.



a)



EXISTING FRAME

Materials: concrete C25/30; steel FeB44 (fyk=430MPa)

Element gross section and strengthening:

Columns	A 30x30 cm	B 35x35 cm	C 30x30 cm
Floor 3	4 ϕ 12	4 ϕ 12	4 ϕ 12
Floor 2	4 ϕ 12	4 ϕ 14	4 ϕ 12
Floor 1	4 ϕ 14	4 ϕ 16	4 ϕ 14
Floor 0	4 ϕ 16	4 ϕ 18	4 ϕ 16

Beams	A - B - C 24x50 cm	AB - BC 24x50 cm
Each floor	5 ϕ 12 3 ϕ 8 2 ϕ 12	3 ϕ 12 3 ϕ 8 4 ϕ 12

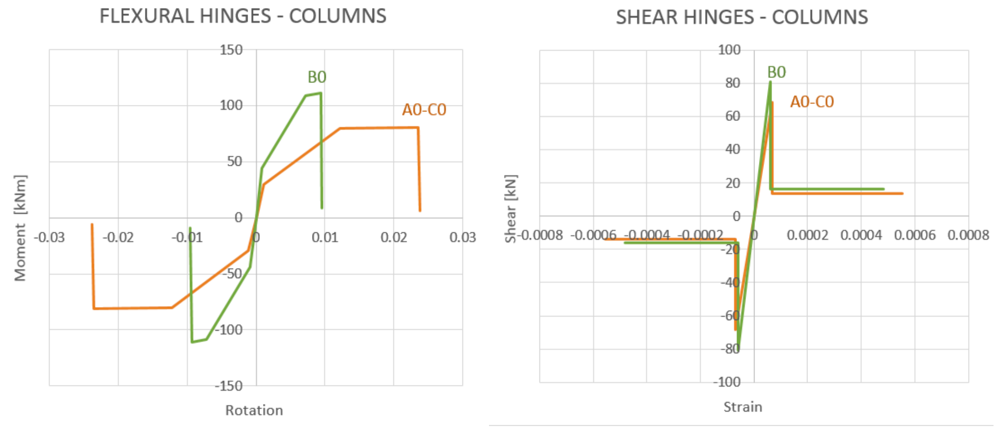
ADDITIONAL SHEAR WALLS

Material: steel S275

Element gross section: Vertical web members: HEA 240

Diagonal and Horizontal web members: HEA 140

b)



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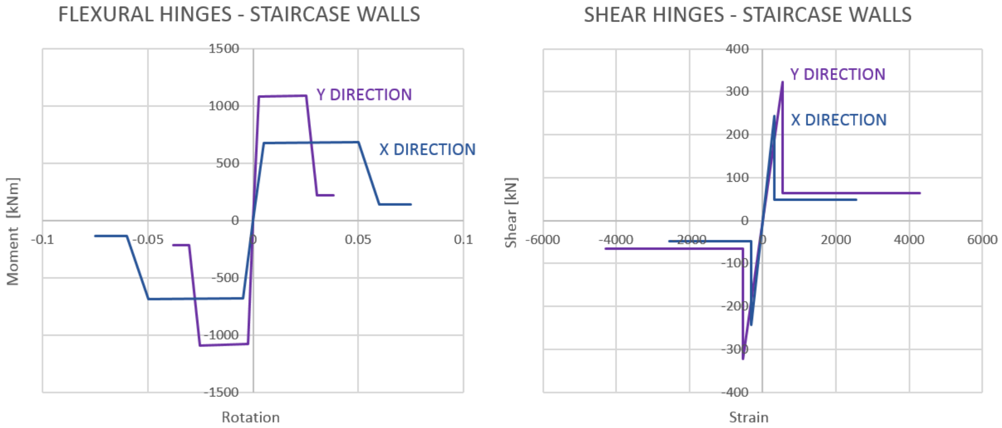

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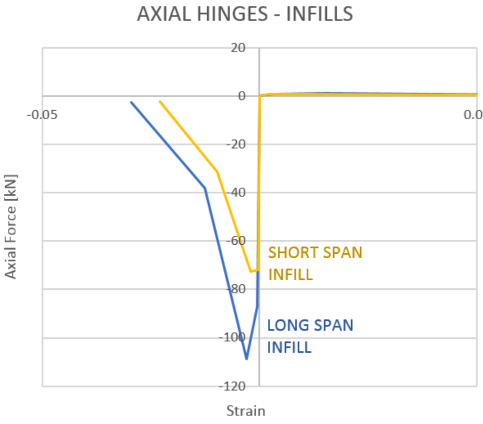


INFILL MODEL [Decanini et al., 1993)

Equivalent strut characteristics:

Long-span infills:	Short-span infills:
E = 1249 MPa	E = 1396 MPa
b = 1432 mm - width	b = 1100 mm - width
t = 130 mm - thickness	t = 130 mm - thickness

e)

Figure 10. a) Schematic plan view of the existing structure (in black) and layout of the shear walls (in red); the dashed red lines represent the deep anchorages or post tensioned tendons needed to connect the new transversal walls to the existing frame; b) main geometrical and mechanical characteristics of the structural elements of the transverse frames; c) flexural and shear plastic hinges of the columns at the ground floor; d) flexural and shear plastic hinges of the staircase walls in the X and Y directions; e) equivalent model of the masonry infills.

The seismic retrofit is designed for the Life Safety Limit State performance level. Beside displacement-based targets calculated according to the Italian Building Code (NTC, 2008), and coherent with EC8 (EN1998.1.1), the damage prevention of the stairwell walls and the control of the shear actions into the existing floors were enforced, in order to protect the only escape path and to avoid the need of introducing floor diaphragms, respectively. In order to meet these additional requirements, the initial stiffness of the building needs to be reduced by some preliminary works.

The conceived global retrofit strategy consists of two steps: in step 1, preliminary interventions, such as those illustrated in Section 4, were applied to reduce the stiffness of the existing structure, to solve the major seismic vulnerabilities, and to obtain a reliable curve of the existing structure (Passoni, 2016); in step 2, new shear walls were added in the two directions.

In step 1, as preliminary interventions, the short pillar vulnerability is solved by disconnecting the basement infill walls and by creating full-height pillars thereby decreasing their lateral stiffness in the longitudinal direction. Moreover, selective weakening is applied to reduce the stiffness of both the staircase (Ireland et al. 2007) and the infill walls (Mohammadi et al. 2011, Preti et al. 2015, INSYSME project 2016). Unless selective weakening was carried out, the stiffness of these elements would be so remarkable that they would collect most part of the seismic action and would fail in a brittle way prior to the activation of the new seismic resistant shear walls, or may require excessively cumbersome additional shear walls; furthermore, such remarkable stiffness would result in excessively large in-plane actions to be transferred across the floor, which in turn would require major strengthening works.

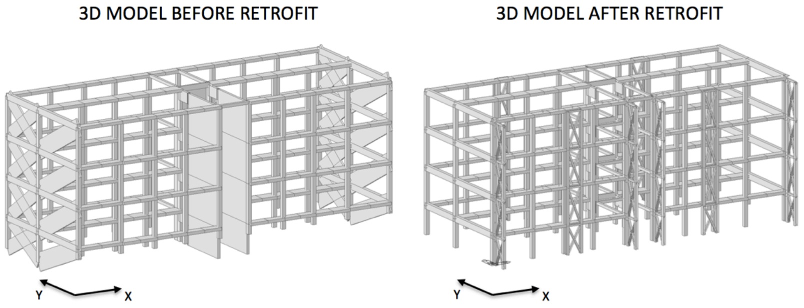
In step 2, shear walls are located in the “depth” of the new exoskeleton as shown in Figure 9 and 10. A steel string course is fixed to the RC ring beams at each floor (horizontal red bands in Fig.9a); the seismic resisting walls are then connected to the existing frames by means of deep anchorages (dashed red line in Fig.10) and steel studs. The new floor of the gallery bridging the shear walls is conceived as a diaphragm to limit the slenderness of the chord of the shear walls, thereby avoiding their global and local buckling (solid red area in Fig.10).

All the shear wall solutions described in section 4 may be adopted and encased in the new exoskeleton; in this simple example, traditional steel shear walls are applied. Four 1.5x0.24m walls, having HEA240 vertical members and HEA140 horizontal and diagonal members (steel S275) were complemented in both the transversal and the longitudinal direction (Fig.11b, left). This mountable and demountable dry technology reduces the disposable material at the end-of-life of the building, fostering the intervention sustainability. The use of steel elements enables a controlled production of the system, providing high quality of the material and sustainability of the production process.

Figure 11a (right) shows the finite element model of the buildings after the intervention. The shear walls components are modelled with truss elements. Given the selective weakening of the stiff elements, the struts modelling the infill behaviour are removed. Also in the case of retrofitted buildings, the floors are assumed to behave like rigid diaphragm (this hypothesis is later verified by assessing that the maximum action in the diaphragm never exceeds the floor in plane capacity).

Figure 11b shows the capacity curve of the retrofitted building, in terms of base shear versus roof displacement in both the transversal and longitudinal direction, compared to that of the existing building in the as-is conditions. After the retrofit the displacement capacity largely exceeds the displacement demand at the LSLS.

As a result of the intervention, the seismic behaviour of the building is significantly improved. The initial stiffness of the structure is reduced as a consequence of the preliminary interventions targeting selective weakening of the stiff elements; those preliminary interventions also prevent the early collapses connected to the onset of the squat column failures and lead to a higher ductility of the existing frame. The strength and the ductility of the retrofitted building are increased through the additional walls. After the retrofit, a more uniform distribution of the interstorey drift can be observed (Fig. 11c). The maximum rotation demand in the RC members never exceeds the rotation capacity, nor the ultimate bending moment is overcome (Fig. 11d). The maximum in-plane action in the floors never exceeds the floor estimated in-plane capacity (see Appendix). Further details on the maximum actions in the structural members and on the proportioning of the seismic resisting shear walls are reported in the Appendix.



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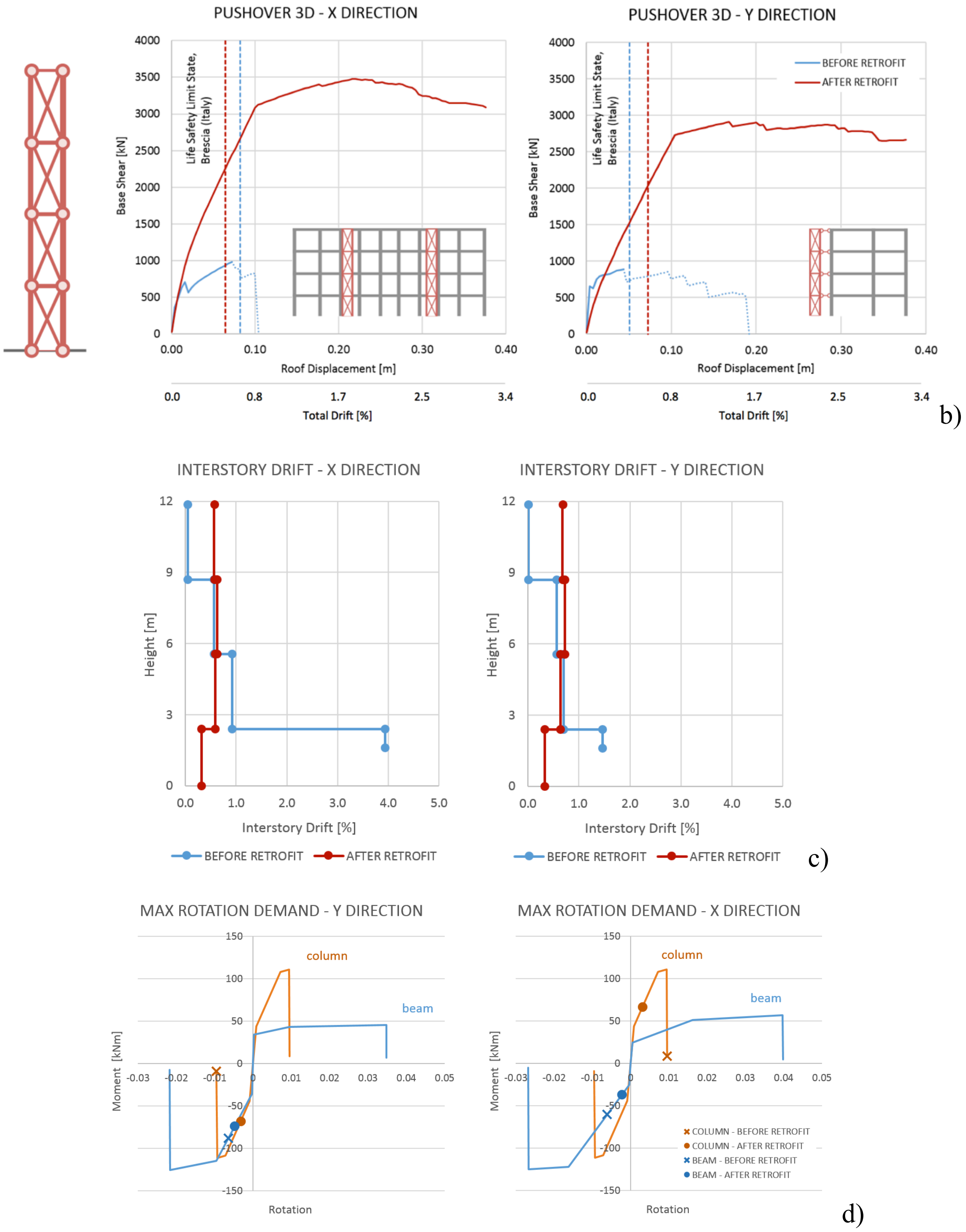

Figure 11. a) Finite element model of the building before (left) and after (right) the intervention; b) additional steel shear walls and seismic capacity of the existing building before and after the intervention in the longitudinal (X) and transversal (Y) directions obtained with a 3D nonlinear static analysis; c) interstorey drift distribution at the Life Safety Limit State displacement demand before and after the retrofit (alignment C of Fig.10a – note that the interstorey drift of the first floor was calculated considering the height of the short columns for the building before the retrofit); d) rotation demand for the most critical beam and column never exceeds the capacity of the structural members.

5.2 Energy upgrade

As regards the energy performance, the main characteristics of the existing building envelope in the as-is condition are investigated. Two brick leaf layers (12+8 cm) with a 6.5cm EPS thermal layer in the cavity and two layers of plaster (1.5cm outside and 1cm inside) constitute the main peripheral walls of the building, except for the space beneath the windows, where the radiators are located and the masonry walls reduced to a double 8+8cm layer without cavity. The existing windows are single glazed with 5cm wood frames.

Major thermal bridges are related to the cavity above the windows due to the presence of rolling shutters and the relief of the RC frame, which projects 12cm above the surface of the infill (Fig. 8b). The horizontal closures of the building have also very poor performances due to the lack of thermal insulation.

Energy audit and balance analyses are carried out to assess thermal performances of the existing envelope in both stationary and dynamic regime, and the efficiency of the heating plant system is analysed. The annual average energy consumption is estimated equal to 194kWh/m^2 per year. The main loss of energy is associated to the high thermal dispersion of the poor insulated opaque and transparent elements especially during the winter. Adopting a minimal intervention strategy, the sole envelope is considered in the energy refurbishment.

The energy retrofit design focuses on the envelope dispersion reduction and on the free solar gain maximization. First, existing windows (2.9W/m^{2}K) are replaced with high-efficiency windows with aluminium frame (1.4W/m^{2}K). Moreover, a new adherent high-performance thermal insulation layer (12cm EPS in the depth of the jutting RC frame + 5cm thick polyester fibre panels) is introduced in the north, east, and west side of the building. Finally, solar greenhouses and shadings are complemented in the exoskeleton expansion along the southern façade. The proposed façade is completely openable in order to allow the ventilation during the summer.

Stationary thermal analyses of the building after the retrofit show that the refurbishment entails a reduction of the heating energy consumption by 70% (56kWh/m^2) and a substantial increase of the solar irradiation with considerable free internal gain (Zanardelli et al. 2014).

The results of the dynamic analysis of the energy balance of the heating system, the solar gain of the exterior windows, and the solar gain of the interior windows are presented in Fig.12. Details can be found in Zanardelli et al. (2014).

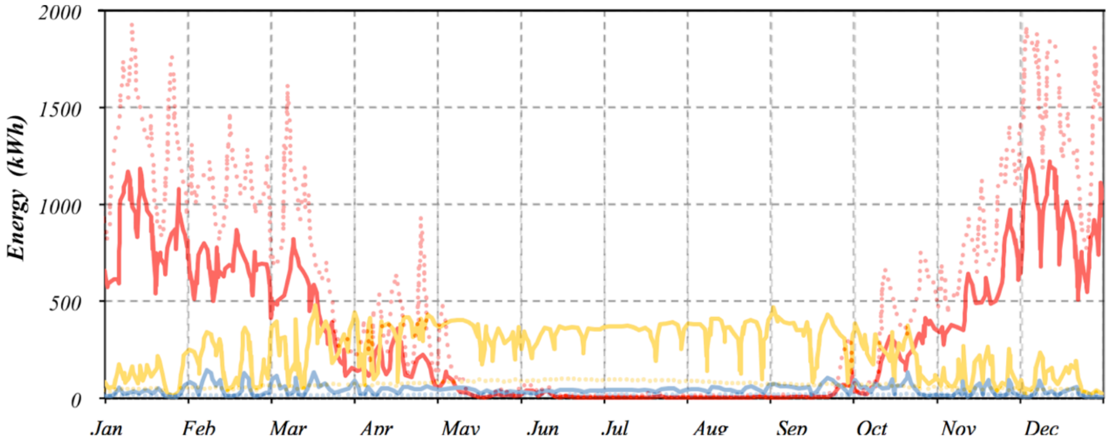

Figure 12. Comparison between the energy balance in the existing building prior (dotted line) and after (solid line) the energy refurbishment in terms of heating system (red) and solar gain of interior (yellow) and exterior (blue) windows (Zanardelli et al. 2014).

5.3 Environmental impact reduction entailed in the integrated renovation

The environmental sustainability of the proposed coupled intervention is pursuit in many ways. The energy consumption and the GHG emissions are reduced by improving the energy performance of the building. A life cycle thinking approach is applied by addressing the end-of-life scenario during the design of the retrofit intervention and by adopting dry, demountable, and easily repairable techniques. Finally, by coupling the seismic retrofit, the intervention reduces the risk of collapse of the building during an earthquake and, as a consequence, the amount of CO_2 emission connected to the demolition of the damaged building, the waste disposal, and the reconstruction of a new building. Applying the procedure presented in Belleri & Marini (2016) the expected annual embodied carbon associated to seismic risk is estimated approximately equal to 4000 kg of CO_2 if seismic interventions are not carried out, and about 400 kg of CO_2 in the case of seismic retrofit. These values could increase up to four times if the same building was located in a region with higher seismicity in the Italian territory.

6. Concluding remarks

A renovation intervention may be considered as effectively sustainable when it is aimed at reducing the environmental impact of a building from the time of the intervention to its end-of-life. Hence, when acting on an obsolete and structurally vulnerable building, energy refurbishment should be coupled to structural and seismic upgrading measures in order to avoid the premature damage, or even collapse, of the building following ageing or seismic events. Starting from this consideration, a proof of concept was carried out for a new generation of sustainable interventions targeting eco-efficiency and resilience, in which structural strengthening is integrated in the renovation process.

Focusing on post-WWII RC buildings, this paper proposed a new holistic renovation approach, in which the exoskeleton of the traditional architectural and energy double skins is further engineered to enable structural safety and improve seismic resilience, and in which the relocation of the inhabitants and the building downtime are minimized by working from outside. Adaptability, easy maintenance and reparability, demountability, and recyclability at the end of life were acknowledged as fundamental objectives of the design for sustainability.

An overview of the possible structural solutions which may be integrated in the engineered exoskeleton was outlined. In particular, shear wall and shell solutions, either dissipative or non-dissipative, were proposed.

The main challenges entailed in coupling seismic intervention to energy refurbishment carried out from outside were analysed. The retrofit design was shown to be substantially affected by the presence of stiff elements, such as infills and stairwells. The role of the floor diaphragms action in collecting and transferring the seismic actions to the lateral force resisting system was highlighted.

After a brief introduction to the topic, the aim of the paper is to highlight the need of integrated approaches to existing building renovation and to foster future collaborations among different stakeholders as civil engineers, energy technologists, and architects among others. To this aim, the concept was thoroughly discussed and a possible application to a reference building was introduced as a proof of the concept. For actual implementation, the proposed technique must be further engineered and adapted to the considered buildings.

The holistic approach to building renovation entails some open issues, generating new research needs. Specific research studies require focusing on: the connections between the exoskeleton and the existing structure; an accurate evaluation of the diaphragm action ensured by the floor in the as-is conditions and the definition of possible floor retrofit solutions when the seismic demand on the retrofitted building exceeds the capacity of existing floors; the conceptual design and experimental testing of innovative ad-hoc dry and demountable solutions to be adopted; new financial solutions to enhance the economic feasibility of the intervention, which should consider both the short term savings arising from the thermal and energy requalification and the long term protection of the investment arising from the structural retrofit.

The study of these topics is beyond the scope of this introductory paper and it is the object of ongoing research.

REFERENCES

Agha Beigi, H., Christopoulos,C., Sullivan, T.J., Calvi,G.M. (2014). Seismic response of a case study soft story frame retrofitted using a GIB system. *Earthquake Eng Struct Dyn*, **44**(7), 997–1014.

Angi, B. (curator). (2016). *Eutopia Urbanscape, The combined redevelopment of social housing*. Ed. Siracusa: LetteraVentidue Ed. Lettera Ventidue. ISBN 9788862421904.

Antonopoulos, C. P. & Triantafillou, T. C. (2003). Experimental investigation of FRP-strengthened RC beam-column joints. *Journal of Composites for Construction*, **7**(1), 39–49.

Belleri, A., and Marini, A. (2016). Does seismic risk affect the environmental impact of existing buildings? *Energy and Buildings*, **110**, 149-158.

Belleri, A., Schoettler M.J., Restrepo J.I., Fleishman R. B. (2014). Dynamic behavior of rocking and hybrid cantilever walls in a precast concrete building. *ACI Structural Journal*, **111**(3), 661-672.

Beschi, C., Riva, P., Metelli, G., Meda, A. (2015). HPFRC Jacketing of Non Seismically Detailed RC Corner Joints. *Journal of Earthquake Engineering*, **19**(1), 25-47.

Christopouolos, C., and Filiatrault, A. (2006). *Principles of Passive Supplemental Damping and Seismic Isolation.* Pavia: IUSS Press.

Decanini, L.D., Gavarini, C., Bertoldi, S.H. (1993). Telai tamponati soggetti ad azioni sismiche, un modello semplificato: confronto sperimentale e numerico. *Atti del VI Convegno Nazionale di Ingegneria Sismica in Italia*, Perugia (in Italian).

Di Ludovico, M., Prota, A., Manfredi, G. and Cosenza, E. (2008), Seismic strengthening of an under-designed RC structure with FRP. Earthquake Engng. Struct. Dyn., **37**: 141–162.

Dolšek, M., Fajfar, P. (2008). The effect of masonry infills on the seismic response of a four-storey reinforced concrete frame—a deterministic assessment. Eng Struct **30**(7), 1991-2001.

EN1998, European Committee for Standardization, “Eurocode 8: Design of structures for earthquake resistance. Part 1: General rules seismic actions and rules for buildings (EN 1998-1:2004)”, Brussels, 2004

Eurostat (2013) *Waste statistics - statistics explain.*

FEMA 398 Incremental Seismic Rehabilitation of Multifamily Apartment Buildings. Risk management series.

Feroldi, F., Marini, A., Badiani, B., Plizzari, G.A., Giuriani., E., Riva, P., Belleri, A. (2013). Energy efficiency upgrading, architectural restyling and structural retrofit of modern buildings by means of “engineered” double skin façade. Proceedings of the 2nd International Conference on Structures & Architecture (ICSA2013) 24-26 July (pp.1859-1866). Retrieved from http://hdl.handle.net/10446/29414.

Feroldi F. (2014). *Sustainable renewal of the post WWII building stock through engineered double skin, allowing for structural retrofit, energy efficiency upgrade, architectural restyling and urban regeneration.* PhD Thesis (In Italian).

Gioiella, L., Balducci, A., Carbonari S., Gara F., Dezi L. (2017). An innovative seismic protection system for existing buildings: external dissipative towers. 16th World Conference on Earthquake Engineering, 16WCEE 2017, Santiago Chile.

Giuriani, E & Marini, A. (2008) Wooden roof box structure for the anti-seismic strengthening of historic buildings. *Journal of Arch. Heritage*, **2**(3), 226-246.

Giuriani, E., Marini, A., Preti, M. (2015). Thin folded shell for the renewal of existing wooden roofs. *Journal of Architectural Heritage,* **10**(6), 797-816.

Guo, J.W.W. & Christopoulos, C. (2013). Performance spectra based method for the seismic design of structures equipped with passive supplemental damping systems. *Earthquake Engineering & Structural Dynamics,* **42**, 935-952.

Hak, S., Morandi, P., Magenes, G., Sullivan, T.J. (2012). Damage control for clay masonry infills in the design of RC frame structures. J Earthq Eng, **16**(suppl 1), 1-35.

INSYSME (2016), Innovative systems for earthquake resistant masonry enclosures in R.C. buildings, Da Porto F. coordinator, European Union’s FP7-SME, grant agreement N. 606229

Ireland, M., Pampanin, S., Bull, D.K. (2006) Concept and Implementation of a Selective Weakening Approach for the Seismic Retrofit of R.C. Buildings. Proceedings of the Annual NZSEE Conference, Napier, New Zealand.

Labò S., Passoni C., Marini A., Belleri A., Camata G., Riva R., Spacone E. (2016). Diagrid solutions for a sustainable seismic, energy, and architectural upgrade of European RC buildings. Proceedings of the XII International Conference on Structural Repair and Rehabilitation. 26-29 October, 2016, Porto, Portugal.

Labò S., Passoni C., Marini A., Belleri A., Camata G., Riva P., Spacone E. (2017). Prefabricated responsive diagrids for holistic renovation of existing mid-rise RC buildings. COMPDYN 2017. 6th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering. Rhodes Island, Greece, 15–17 June 2017. M. Papadrakakis, M. Fragiadakis (eds.)

Loonen, R. C. G. M. (2015), Bio-inspired Adaptive Building Skins, in Biotechnologies and Biomimetics for Civil Engineering, Springer International Publishing.

Manfredi, G., Ricci, P., Verderame, G.M. (2012). Influence of infill panels and their distribution on seismic behavior of existing reinforced concrete buildings. Open Constr Build Technol J, **6**(Suppl 1–M1): 236-253.

Marini, A. & Meda, A. (2009), Retrofitting of r/c shear walls by means of high performance jackets, *Engineering Structures*, **31**(12), 3059-3064.

Marini, A., Passoni, C., Riva, P., Negro, P., Romano, E., Taucer, F. (2014). Technology options for earthquake resistant, eco-efficient buildings in Europe: Research needs, *Report EUR 26497 EN. JRC87425*. ISBN 978-92-79-35424-3. doi:10.2788/68902. Publications Office of the European Union.

Marini A., Passoni C., Belleri A., Feroldi F., Preti M., Riva P., Giuriani E., Plizzari G. A. (2016). Need for coupling energy refurbishment with structural strengthening interventions. *In: Eutopia Urbana. Eutopia Urbanscape. The combined redevelopment of social housing*, edited by Barbara Angi. ISBN: 978-88-6242-190-4.

Martinola, G, Meda, A, Plizzari, G., Rinaldi, Z. (2007). An application of high performance fiber reinforced cementitious composites for R/C beams strengthening. Proceedings *FRAMCOS 6*. Catania (Italy), 18-21.

Masboungi, A. (curator) (2005). *Régénérer les grands ensembles*.Ed. de la Villette, Paris.

Metelli, G. (2013). Theoretical and experimental study on the cyclic behaviour of X braced steel frames. *Engineering Structures,* **46**,763–773.

MidasGen (2015, v2.1). Copyright © SINCE 1989 MIDAS Information Technology Co., Ltd.

Mohammadi, M., Akrami, V., Mohammadi-Ghazi, R., (2011). Methods to Improve Infilled Frame Ductility, *Journal of Structural Engineering* **137**(6), 646-653.

Montuori, M., Lupo, G., Muraca, A., Longo, O., Angi, B., Botti, M., Orsini, F. (2009). Nuove pratiche progettuali per la riqualificazione sostenibile di complessi di habitat sociale in Italia. University of Brescia.

NTC (2008). Norme tecniche per le costruzioni, D.M. 14 Gennaio 2008 (Italian Code).

Pampanin, S. (2012). Reality-check and renewed challenges in earthquake engineering: implementing low-damage systems – from theory to practice. *Bulletin of the New Zealand society for earthquake engineering*, **45**(4), 137-160.

Passoni, C. (2016). *Holistic renovation of existing RC buildings: a framework for possible integrated structural interventions*, Ph.D. thesis, University of Brescia.

Preti, M., Migliorati, L., Giuriani, E. (2015). Experimental Testing of Engineered Masonry Infill Walls for Post-earthquake Structural Damage Control, *Bulletin of Earthquake Engineering*, **13**(7), 2029-2049.

Preti, M., Bolis, V., Cominelli, S., Loda, S., Marini A., Giuriani, E. 2017. Dissipative roof diaphragm for the seismic retrofit of listed masonry churches. Accepted for pubblication in the Journal of Earthquake Engineering.

Qu, Z., Wada, A., Motoyui, S., Sakata, H., Kishiki S. (2012). Pin-supported walls for enhancing the seismic performance of building structures. *Earthquake Engineering & Structural Dynamics*, **41**(14), 2075–2091.

Riva, P., Perani, E., and Belleri, A., “External R.C. Structural Walls for the Repair of Earthquake Damaged Buildings”, Sustainable Development Strategies for Constructions in Europe and China, Rome 19-20 April 2010.

Takeuchi, T., Yasuda, K., and Iwata, M., (2009). Seismic Retrofitting using Energy Dissipation Façades. *Proceedings of ATC & SEI Conference on Improving the Seismic Performance of Existing Buildings and Other Structures*, 1000-1009.

Trombetti T., Silvestri S., (2007), Novel schemes for inserting dampers in shear-type systems based upon the mass proportional component of the Rayleigh damping matrix, *Journal of Sound and Vibration*, **302**(3): 486-526.

Xu, Y.L., He Q., Ko J.M. (1999). Dynamic response of damper-connected adjacent buildings under earthquake excitation, *Engineering Structures*, **21**(2) 135–148.

Zanardelli, M., Belardi, M., Marini, A., Feroldi, F., Plizzari, G.A. (2014). Riqualificazione energetica, architettonica e strutturale del costruito esistente: aspetti energetici, *Technical Report*, DICATAM, University of Brescia.

Wada, A., Qu, Z., Ito, Motoyui, S., Sakata, H., Kasai, K. (2009) Seismic Retrofit Using Rocking Walls and Steel Dampers. *ATC/SEI Conference on Improving The Seismic Performance of Existing Buildings and Other Structures San Francisco, CA*, U.S., Dec. 2009

APPENDIX

Evaluation of the in-plane capacity of the floors.

With reference to the preliminary results of the research by Passoni 2016, and Feroldi 2014, and to the proposed simplified model for the evaluation of the in plane capacity of existing composite beam and block floors, the capacity of the examined floor was estimated by considering the capacity of the arch-and-tie system developing within the floor thickness and bridging the distance between the shear walls. The ultimate capacity of the arch can be bound to (Fig. A1a): a) the failure of the blocks at the midspan, where they are compressed along the weakest direction, orthogonal to the hollows, b) the failure of the interface between the RC beam and the clay block, and c) the tensile failure of the tie (corresponding to either the failure of the brick-to-RC beam interface for overcoming adhesion or the brick traction resistance, or the tensile failure of the edge beam for overcoming the traction resistance of the RC element). In the analysed example, the use of a steel string course inhibits failure c), the high rise of the arch inhibits mechanism a) and failure b) is the most critical.

The average experimental equivalent ultimate shear stress along the interface between the beam and the blocks was shown to be approximately equal to τ_u=1.72MPa

(Passoni 2016 and Feroldi 2014). By adopting this value, the maximum in-plane shear resistance is equal to $V_f = 0.5\ \tau_u\ H\ t_{eq} = 310kN$, where $t_{eq} = 35mm$ is the net thickness of the brick (equal to 4 thin clay diaphragms, excluding the hollow thickness), H =10.3m is the height of the floor.

In the analysis the maximum action transferred to the shear wall is equal to $F_{w2,X} = 159kN$ in shear wall at floor level n. 2 in the X direction. Provided that $F_w < V_f$ the floor is then assumed to behave like a rigid diaphragm (i.e.. the stiffness is very high, and the diaphragm may be assumed as rigid if its strength is sufficient).

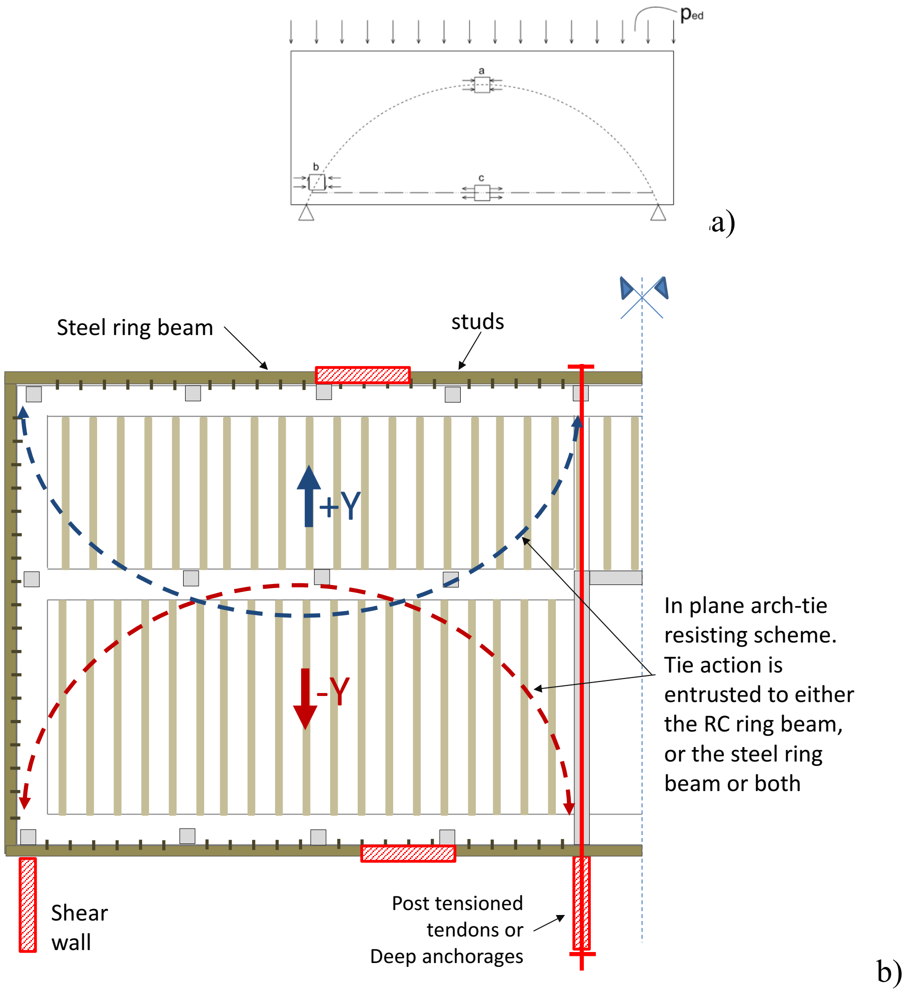

Figure A1. a) Schematic representation of the arch and tie system developing in the existing floor and possible critical portions which may experience failure; b) schematic representation of the floor structural components; c) example of tendons and shear connections fixing the shear walls to the existing floors.

Preliminary evaluation of the connection of the shear walls to the existing buildings

Connection of the shear walls to the existing building must be guaranteed through deep anchorages, post tensioned rigid ties and studs or special devices, also exploiting the multipurpose steel ring course (Fig A1b).

To allow transferring the maximum shear action $F_{w2,X} = 159kN$ at the floor level n. 2 to the shear wall in the X direction, n.8 d20 steel studs, each having a maximum design resistance of 20kN may be adopted.

To allow transferring the maximum shear action $F_{w3,Y} = 151kN$ at the floor level n. 3 to the shear wall close to the stairwells in the Y direction, a post tensioned rigid tie is adopted; to avoid detachment of the shear wall from the diaphragm in case of seismic action acting in the +Y direction, the tendon is post tensioned to a stress higher than the maximum force arising from the seismic excitation. The ties can be located at the ceiling level, to prevent damaging the pavements. Ties are fixed with steel plates at the steel ring course.

Maximum actions in the shear wall members

The maximum actions in the shear wall members at the LSLS demand are summarized in table A1.

Table A1. Maximum actions in the shear wall members

		Y DIRECTION	X DIRECTION
		ground floor	ground floor
Internal actions:	Vertical member (L=2.4m)	N = 1567 kN	N = 1448 kN
	Diagonal member (L=2.7m)	N = 450 kN	N = 443 kN
		first floor	first floor
	Vertical member (L=3.15m)	N = 810 kN	N = 697 kN
	Diagonal member (L=3.4m)	N = 387 kN	N = 386 kN
Reaction forces at the most loaded shear wall base.	Axial force	N = 1968 kN N = - 1943 kN	N = 1843 kN N = - 1819 kN
	Shear	N = 410kN	N = 405kN

Foundation

The shear wall foundations can be designed with n.4 d240mm vertical micropiles (each having a maximum axial capacity of N_{mp} = 900kN), transferring the vertical reaction force of each vertical member of the shear wall, and n.2 d240mm inclined micropiles, transferring shear.

Response spectrum

The Response Spectrum at the Life Safety Limit State, calculated according the Italian Building Code (NTC, 2008), and coherent with EC8 (EN1998.1.1), for the city of Brescia is given in Figure A2.

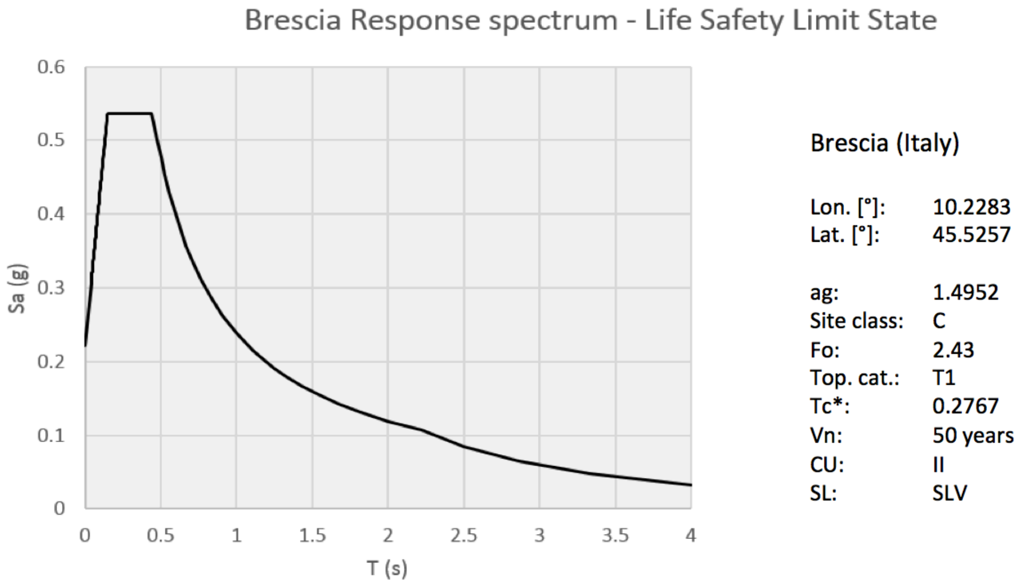

Figure A2. Response Spectrum at the Life Safety Limit State calculated according the Italian Building Code (NTC, 2008), for the Italian city of Brescia.