Integrated, sustainable, low-impact retrofitting through exoskeleton structures: a case study

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ABSTRACT
Improvement of safety and eco-efficiency of existing buildings is an interdisciplinary problem: this is an established, although recent, research and policy acquisition. The age profile analysis of the EU's building heritage reveals that the main part of this 27 billion m^2 stock was built between 1961 and 1990, and a significant percentage before 1960. Poor thermal and environmental performances, as well as the failure to comply with modern seismic design codes, are common problems that require an integrated solution approach (Caverzan et al. 2016). In this context, exoskeleton structures appear to be a promising retrofitting strategy due to a number of reasons: the potential for a multifunctional design combining structural safety, energy efficiency and environmental sustainability; limited interference with existing structural and nonstructural components; minimal service or business downtime during the retrofitting process (Reggio et al. 2018).
In this paper, a case study is presented, dealing with the integrated, seismic and energy, retrofitting of a mid-rise building, located in the city of Torino (Italy). The existing structure, a non-ductile reinforced concrete frame, is coupled via a rigid connection to an exoskeleton structure, realised as a steel braced frame. The exoskeleton structure is set adjacent to the existing structure and designed in order to reduce the seismic response of the latter, in terms of displacements and internal forces. In the perspective of an integrated design approach, the exoskeleton structure is further used to support external thermal insulation panels, aimed at the energy upgrading of the building envelope. Possible interference and synergies between seismic and energy retrofitting requirements are highlighted and discussed.

1 INTRODUCTION

The age profile analysis of the EU's building heritage reveals that the main part of this 27 billion m^2 stock was built between 1961 and 1990, and a significant percentage before 1960. Poor thermal and environmental performances, as well as the failure to comply with modern seismic design codes, are common problems that require an integrated solution approach (Caverzan et al. 2016). On the one hand, green building practices have to be implemented with an understanding of their interactions with structural performance and durability, in such a way that they do not compromise the building's resistance to natural hazards like earthquakes (FEMA P-798 2010). On the other hand, seismic risk affects the environmental impact of existing buildings: it could impair the energy savings and money investment obtained with solely energy retrofitting interventions, besides being a safety threat (Belleri and Marini 2016).

In the framework of the Italian Earthquake Engineering community, it is worth mentioning the recently launched project ReLUIS-DPC 2019-2021 (ReLUIS 2019), funded by the Italian Civil Protection Department, and particularly the project Work Package number 5 (WP5), aptly titled "Rapid, low-impact and integrated interventions". Addressing the objectives of ReLUIS 2019 WP5, the research unit at Politecnico di Torino has developed a case study dealing with the integrated, seismic and energy, retrofitting of an existing building by way of an exoskeleton structure. Exoskeleton structures currently represent one of the most interesting and sustainable holistic approaches to building retrofitting. An exoskeleton structure can be properly defined as a self-supporting structural system set outside and suitably connected to a primary inner structure, the latter being enhanced or protected, in a general sense, by virtue of this connection. In seismic prone areas, it is conceived as a “sacrificial” appendage, called to absorb seismic loads in order to control the dynamic response of the primary inner structure (Reggio et al. 2017a, 2018b). Its potential for a multifunctional design, combining structural safety, energy efficiency and environmental sustainability, is particularly attractive. Further advantages can be envisaged: limited interference with existing structural and nonstructural components; minimal service/business downtime during the retrofitting process, as the intervention is operated from the outside; consequent limited cost.

This research work presents and discusses the results from preliminary analyses conducted on the above-mentioned case study, developed at Politecnico di Torino. The case study concerns a mid-rise building, whose resisting structure is a low-ductility reinforced concrete frame. The proposed retrofitting intervention consists in rigidly coupling the existing structure to an exoskeleton structure, realised as a steel braced frame. The design of the exoskeleton structure takes into account both structural and energy considerations, with a twofold objective: from the seismic point of view, to reduce the earthquake response of the existing structure, in terms of displacements and internal forces; from the energy point of view, to cut down the operational energy consumption by upgrading the building envelope.

2 CASE STUDY

2.1 *Existing building*

The case study refers to a social housing building, located in the city of Torino (Italy) and built in 1955 (Figure 1). The building has 6 storeys, of which one basement, with rectangular plan of dimensions 30 m x 12 m and area 360 m^2. Inter-storey height is 3.25 m. The existing structure is a reinforced concrete moment-resisting frame, characterised by very low ductility level, as expected according to the Italian regulatory building code dating back to the construction period. Four reinforced concrete shear walls are placed along the transverse direction of the building, encasing two stairwells. Mass and stiffness distributions satisfy criteria for regularity in plan and in elevation (EN 1998-1:2004, NTC 2018).

Figure 1. Aerial view of the case study building.

A Finite Element (FE) model (Figure 2a) of the existing structure has been developed by employing the structural analysis program SAP2000 v.20 (Computers & Structures 2018). Floor slabs, realised as hollow bricks and reinforced concrete slabs, have been verified to have an in-plane rigid behaviour, entailing the introduction of a diaphragm constraint at each floor level.

2.2 *Seismic retrofitting*

2.2.1 *Exoskeleton structure*

The proposed seismic retrofitting intervention consists in coupling the existing structure to an exoskeleton structure, set adjacent to the former and provided with an independent foundation.

The exoskeleton structure has been designed as a steel braced frame. Single-storey X-braces occupy 13 bays over the 21 bays available in total; their layout has been chosen taking into account the presence of existing entrances and balconies. A heuristic design process, drawing on a performance index defined in terms of displacement response, has led to select the following cross sections for the different structural elements: HEA 200 columns, HEA 100 horizontal beams, HEA 200 bracing diagonal beams. In the FE model of the coupled system (Figure 2b), the exoskeleton structure is connected to the existing structure at each storey level by way of rigid links.

a.

b.

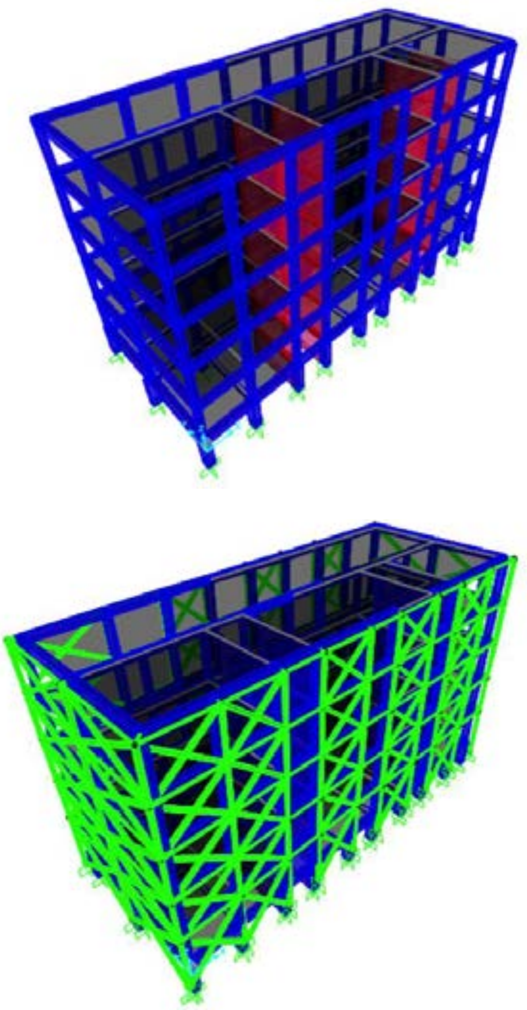


Figure 2. FE models of: a. bare existing structure; b. coupled system, i.e., existing structure coupled to the exoskeleton structure.

2.2.2 *Vibration properties*

Tables 1 and 2 report periods and participating mass ratios of the first three natural vibration modes, respectively, of the bare existing structure and of the coupled system (i.e., the system given by the existing structure coupled to the exoskeleton structure).

Table 1. First three natural vibration modes of the bare existing structure: periods and participating mass ratios.

Mode	T [s]	M_x [%]	M_y [%]	R_z [%]
1	0.925	71.00	0.00	0.05
2	0.505	0.05	0.45	62.59
3	0.373	0.00	61.49	0.47

Table 2. First three natural vibration modes of the coupled system: periods and participating mass ratios.

Mode	T [s]	M_x [%]	M_y [%]	R_z [%]
1	0.494	67.97	0.00	0.34
2	0.310	0.02	59.04	4.63
3	0.269	0.35	4.75	63.32

From Tables 1 and 2, a substantial uncoupling between translational modes in longitudinal (x) and transverse (y) direction and rotational modes emerges. Hence, both the bare existing structure and the coupled system can be considered as symmetrical in plan with respect to orthogonal axes x and y. A general reduction of natural vibration periods is observed in the coupled system compared to the bare existing structure: the period of the first translational mode in x-direction drops from 0.925 s to 0.494 s, with a reduction of about 47%; the period of the first translational mode in y-direction drops from 0.375 s to 0.310 s, with a reduction of about 17%.

2.2.3 *Seismic analyses*

Seismic analyses have been carried out on the FE models of the bare existing structure and of the coupled system, in order to compare their response under earthquake loading.

Seismic hazard has been described according to the current Italian Building Code (NTC 2018). Considering the geographic coordinates and soil class (B, or deposits of very dense sand) of the existing building site, the reference peak ground acceleration at bedrock is: for the Damage Limitation performance requirement, $a_g = 0.027\ g$, being g the gravity acceleration, having a probability of exceedance of 63% in 50 years (mean return period 50 years); for the Life Safety performance requirement, $a_g = 0.052\ g$, having a probability of exceedance of 10% in 50 years (mean return period 475 years). The relevant elastic pseudo-acceleration response spectra (5% viscous damping) are shown in Figure 3.

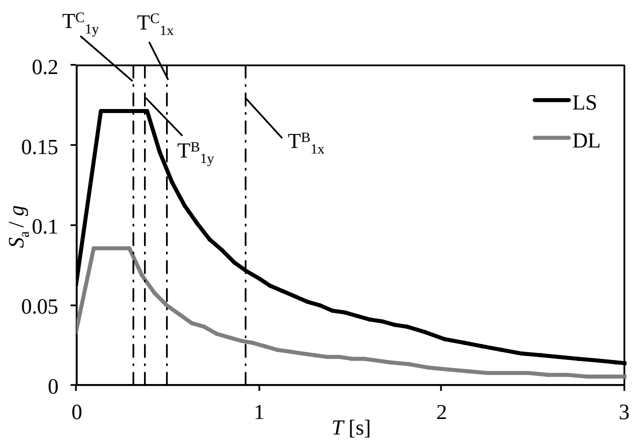


Figure 3. Elastic pseudo-acceleration response spectra (5% viscous damping) defined for the Life Safety (LS) and Damage Limitation (DL) performance requirements, according to the Italian Building Code (NTC 2018). Dash-dot lines indicate periods of the first translational modes in x- and y-direction for the Bare (B) existing structure and for the Coupled (C) system.

Results obtained by response spectrum analyses are shown in Figures 4-6 and discussed below. The illustrated response quantities of interest are floor displacements relative to ground and floor shear forces. From the view point of seismic protection, they represent indeed the engineering demand parameters which deformation-sensitive, structural and non-structural, damage correlate with.

Figure 4 illustrates the variation of peak floor displacements along the height of the existing structure, both bare and coupled to the exoskeleton structure, at the Life Safety limit state. The displacement response of the existing structure appears to be significantly reduced, over its entire height, by virtue of the rigid coupling to the exoskeleton structure. In *x*-direction, reductions of peak floor displacements range from 50% to 43%, decreasing with the increasing floor level. Floor displacements in *y*-direction are smaller than the ones in *x*-direction, yet for the bare existing structure due to the stiffening effect of shear walls. For the coupled system, reductions range from 28% to 34 %, increasing with the increasing floor level.

Figure 5 depicts the profiles of peak floor shear forces along the height of the existing structure and of the exoskeleton structure, for both the horizontal directions, at the Life Safety limit state. Broadly speaking, the rigid coupling to the exoskeleton structure may lead to an increase of total floor shear forces, because of the larger mass and of the reduced vibration periods of the coupled system, compared to the bare existing structure. Nevertheless, due to the kinematic constraint deriving from the rigid coupling, total floor shear forces are split among the existing structure and the exoskeleton structure. By considering only the portion of floor shear forces resisted by the existing structure, and by comparing profiles related to its bare and to its coupled configuration, significant reductions are observed. In *x*-direction (Figure 5a), shear forces are reduced at all floor levels except the last one, where a slight increment is conversely obtained. The reduction of base shear, in particular, amounts to 48%. In *y*-direction (Figure 5b), floor shear forces are reduced over the entire height of the existing structure, although reduction values are globally lower than in *x*-direction. The reduction of base shear, in particular, amounts to 15%, while the reduction value at the last floor level is 58%.

As highlighted by the obtained reductions of base shear, the proposed seismic retrofitting approach has the noteworthy advantage of avoiding the strengthening of the foundation below the existing structure.

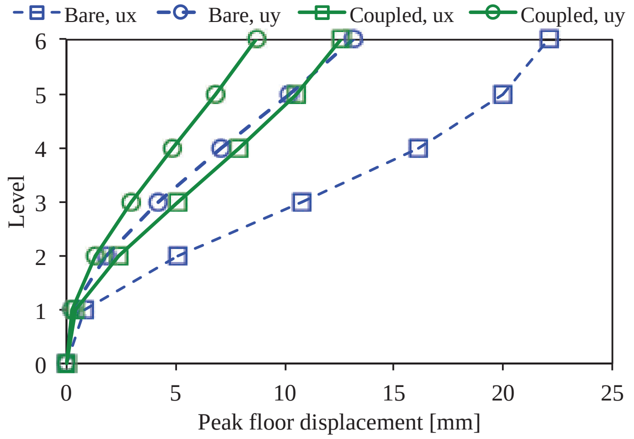
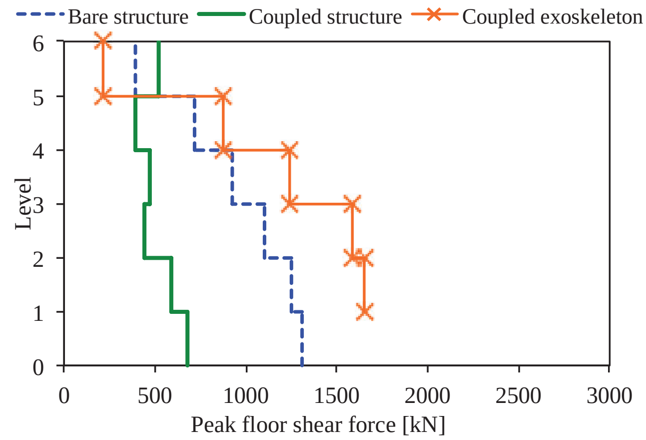


Figure 4. Profiles of peak floor displacements in *x*- and *y*-direction, comparisons between bare existing structure and coupled system. Life Safety limit state.

a.



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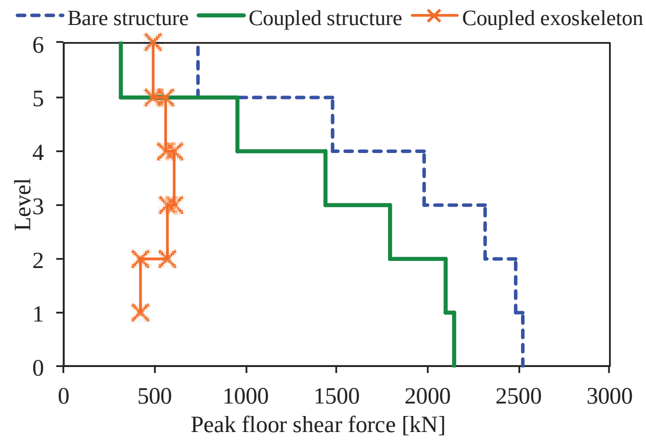
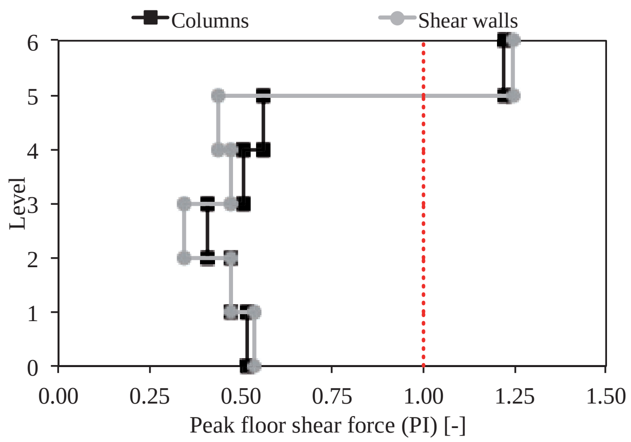


Figure 5. Profiles of peak floor shear forces on the bare existing structure and on the coupled system in: a. *x*-direction; b. *y*-direction. Life Safety limit state.

a.



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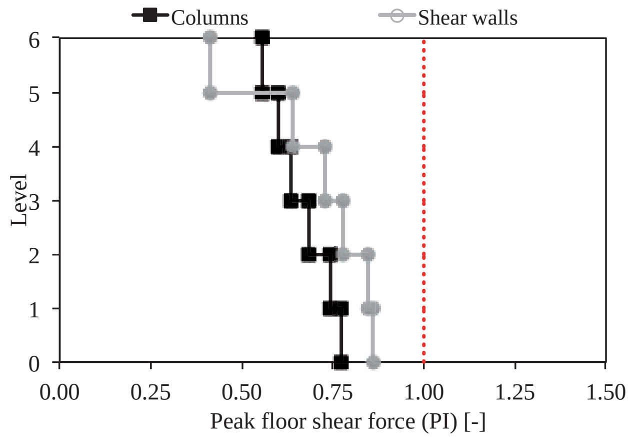

Figure 6. Performance indices (PI) related to the peak floor shear forces on columns and shear walls of the existing structure: a. *x*-direction; b. *y*-direction. Life Safety limit state.

To get a more in-depth insight into the shear demand on the existing structure, the distribution of floor shear forces between columns and shear walls has been investigated. In Figure 6, relevant performances indices are presented. The Performance Index (PI) is defined as the ratio of the peak floor shear force between the coupled system and the bare existing structure: a value smaller than one corresponds to a reduction of the shear force in the coupled system compared to the bare existing structure, while a value greater than one means an amplification. From the profiles in figure, the following considerations can be drawn. In *x*-direction (Figure 6a), values of PI on columns and shear walls are substantially comparable; in *y*-direction (Figure 6b), where the maximum moment of inertia of the shear walls is mobilised, values of PI are generally lower on columns than on shear walls, indicating that a higher effectiveness in reducing the shear demand is achieved on columns.

2.3 *Energy retrofitting*

2.3.1 *Energy performance assessment of the existing building*

The energy performance assessment of the existing building has concerned only the characteristics of the building envelope, which is the target of the retrofitting intervention through the exoskeleton structure.

The assessment has been carried out on the basis of the “National Building Typology” database, available for the Italian building stock (Corrado et al. 2014). Input data for the existing building are: climatic zone E (Heating Degree Days 2617); construction period 1946-1960; building dimension class apartment block; gross volume 6075 m^3 and gross floor area 1800 m^2. Based on this data, the thermo-physical parameters of the existing building envelope can be estimated through the use of a reference building, selected from the above-mentioned database and characterised by the same climatic zone, dimension class, geometry and boundary conditions. Values of thermal and solar energy transmittance obtained for the opaque and transparent components of the existing building envelope are reported in Table 3. Symbol *U* denotes the thermal transmittance, symbol *G* denotes the total solar energy transmittance.

Table 3. Energy performance assessment of the existing building.

Component	Performance parameter		
Opaque envelope	U_{op}	[W m^{-2} K^{-1}]	1.26
Windows	U_w	[W m^{-2} K^{-1}]	4.90
	$G_{gl,n}$	[–]	0.85
Doors	U_w	[W m^{-2} K^{-1}]	5.70
	$G_{gl,n}$	[–]	0.85

2.3.2 *Energy retrofitting design*

The proposed energy retrofitting intervention deals with the upgrading of the building envelope, is aimed at the reduction of the operational energy consumption and consists in the following two energy efficiency measures:

1. regarding the opaque envelope, the realisation of a thermal insulation placed outside the exoskeleton structure;
2. regarding the transparent envelope, the replacement of the existing windows with high energy efficiency ones.

According to the current Italian regulatory code (D.M. 26.06.2015), such an intervention is classified as "second level" because it affects the building envelope for more than 25% of its gross area. Based on this classification, the same code provides the minimum energy performance requirements that have to be satisfied in the design of the retrofitting intervention.

Regarding the first energy measure, we observe that, if the thermal insulation layer was placed in adherence to the existing structure, thermal bridges would arise corresponding to the discontinuities between steel elements of the exoskeleton structure and insulation layer. Conversely, to ensure the continuity of the insulation layer, the proposed design choice is to set it *outside* the exoskeleton structure. We recall that, in the design of the exoskeleton structure, the same cross section (HEA 200) was selected for columns and bracing beams. Motivation was not limited to structural considerations, but indeed met the need of having a continuous support plane for the easy fixing of the thermal insulation layer.

The scheme of the retrofitted opaque building envelope is illustrated in Figure 7. The sequence of strata, numbered from outside to inside as in figure, includes: (1) thermal insulation panel, rock wool, thickness 12 cm; (2) 20 cm deep air gap, corresponding to the depth of the exoskeleton structure; (3) 12 cm deep solid bricks; (4) 2 cm thick cement mortar; (5) 8 cm deep solid bricks; (6) 6 cm deep air gap; (7) 10 cm deep hollow bricks; (8) 2 cm thick inside plaster. Strata from (3) to (8) constitute the opaque envelope of the existing building. For the thermal insulation layer (1), rock wool rigid panels with design thermal conductivity $\lambda_D = 0.035\ \mathrm{W m^{-1} K^{-1}}$ are used and their thickness has been designed on the basis of code requirements.

The thermal transmittance of the retrofitted opaque building envelope has been computed by employing the software Pan 7.0 (ANIT 2019). Comparisons between *pre* and *post* energy retrofitting values are reported in Table 4. Verifications of the requirements from the current Italian regulatory code are fully satisfied, concerning: the limit thermal transmittance of the opaque (U_{op}) and transparent (U_w) components of the building envelope; the limit total solar energy transmittance of glass and shading devices G_{gl+sh}; the maximum mean thermal transmittance of the building envelope, or the so called "global transmission heat transfer coefficient" (H'_T).

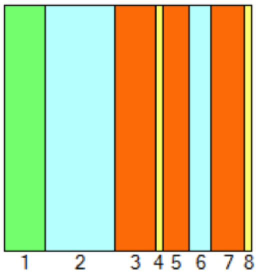

Figure 7. Scheme of the retrofitted opaque building envelope.

Table 4. Energy performance assessment of the retrofitted building.

Component	Performance parameter		Pre	Post
Opaque envelope	U_{op}	[W m^{-2} K^{-1}]	1.08	0.22
Windows	U_w	[W m^{-2} K^{-1}]	4.90	0.84
	G_{gl+sh}	[–]	–	0.18
Doors	U_w	[W m^{-2} K^{-1}]	5.70	1.26
Building envelope	H'_T	[W m^{-2} K^{-1}]	–	0.58

3 CONCLUSIONS

In this paper, a sustainable and low-impact strategy to the integrated seismic and energy retrofitting of existing buildings has been investigated. The strategy consists in rigidly coupling the existing structure that needs to be retrofitted with a newly built self-supporting exoskeleton structure, set adjacent to the former. The exoskeleton structure can be purposely designed to protect the existing structure under earthquake loading, as well as to meet further retrofitting functions, in terms of energy efficiency, environmental sustainability and architectural quality. Not least, retrofitting operations can conducted, almost totally, from outside the building, thus limiting the impact on service and business continuity.

The research work has focused on a case study, dealing with the integrated retrofitting of a mid-rise low-ductility reinforced concrete frame coupled to a steel braced frame exoskeleton structure. The results obtained from preliminary analyses have highlighted a significant displacement and internal force control of the existing structure. The achieved control performance depends on the dynamic properties exhibited by existing structure and exoskeleton structure, hence it could be affected by the presence of stiffening elements in the existing structure, such as shear walls. Synergies between seismic and energy retrofitting requirements have been pointed out and deliberately exploited, proving the efficacy and cost efficiency of the proposed integrated approach.

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