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The exoskeleton: a solution for seismic retrofitting of existing buildings

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Abstract

An exoskeleton is an external steel self-supporting system rigidly linked to an existing building that need to be safeguarded against seismic actions in order to comply with the current technical standards. Its application can guarantee an innovative seismic adjustment that combines structural and safety goals with sustainable properties. The present study deals with the performances of the developed coupled system under seismic actions when a suitable exoskeleton structure is applied to a real construction. It is designed with an in-plane rigid behaviour at each floor and a non-dissipative rigid link connects the primary building to the external structure. Early descriptions of the inner and the external constructions forerun the dynamic analysis, which allows to understand seismic response of the system especially in terms of frequencies and periods of vibration, floor displacements, stiffness and shear forces. Ensuing outcomes highlight the capability the exoskeleton has in taking base and floor shear forces as well as in reducing displacements and deformations of the primary building, so that it is protected from a potential earthquake collapse.

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Keywords: Coupled system; exoskeleton structure; seismic adjustment; structural dynamics

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1. Introduction

Any kind of construction is source of considerable effects to the environment, no matter what it has been designed for. As reported in the Document for E2B European Initiative (2012), more than a third of total greenhouse gas emissions derives from them; in parallel, this energy-intensive field represents the "second largest untapped cost-effective potential for energy savings after the energy sector". Thus, innovative ideas and advanced technological solutions should light the way to take safer and more sustainable measures that must be applied above all to existing buildings. A similar situation occurs considering other European countries.

The rich variety of styles and designated uses of the Italian building heritage makes it stand out, but they share a common aspect: they are generally outdated. In fact, it has been proved that almost 61% of them has already exceeded the designed lifespan of 50 years as illustrated by ISTAT census (2011). The outcome is significant because the prevalence of buildings devoid of an adequate seismic design and energetic monitoring is evident; so, safety assessment and structural vulnerability have finally taken a leading role. The aim of the present study consists of investigating the seismic performance of steel exoskeleton structures and the way they succeed in controlling earthquake induced vibrations of existing reinforced concrete buildings.

The expression *exoskeleton structure* indicates a self-supporting structural system put in the exterior part of an existing construction which is linked to. The chosen connection also represents the way the inner building can unload itself giving the stresses to the steel external frame, which is essentially designed to protect the first one as described by Belleri et al. (2016), Caverzan A. (2016) and Marini A. (2014). Researchers have now become more interested in this kind of solution trying to guarantee not only retrofitting renovations like those related to energy efficiency, architectural renewal or environmental sustainability, but especially in engineering approaches: it is necessary that anti-seismic strategies join the previous subjects, as reported by Reggio et al. (2019). External structures allow to reduce business downtime and to avoid residents' relocation thanks to the operative processes that are done from the outside; they can also enhance economic and environmental effectiveness of the resulting system by updating the structure to the current sustainable needs; moreover, they restore the designed lifetime bringing also a new aesthetic shape and additional housing or public spaces can be provided as well. The exoskeleton is added to bear seismic loads aiming at protecting the existing frame structure and preventing its damage during earthquake actions. A rigid link is assumed to connect the two independent structures whose masses are not negligible so, as outlined by Reggio et al. (2019), a dynamic coupling has been considered.

The paper is organized as follows.

After this Introduction, Section 2 focuses on a theoretical description of the system composed by two coupled linear viscoelastic oscillators based on their dynamic model. A more detailed case study is carried on in Section 3: firstly, the primary existing building, then its seismic adjustment. Subsections 3.3 and 3.4 concern dynamic results of both models comparing each other; conclusions are finally explained in Section 4.

2. Theoretical model

Aiming at carrying out a dynamic analysis, it is possible to discretize the existing building into a planar frame made up of rigid stories whose masses are centred on each horizontal level, instead of stiffness which is referred to the columns that connect each floor to the other. A theoretical simplification consists of getting the system equivalent to a simple oscillator with one degree of freedom, i.e. mass is concentrated in a single point, a spring without mass holds all the stiffness and a damper makes energetic dissipation possible, as detailed by Martelli L. (Master Degree Thesis, 2018).

So, without lack of generality, the resulting system composed by a primary structure linked to an exoskeleton structure is modelled by means of two coupled linear viscoelastic oscillators, as reported by Reggio et al. (2019). In fact, the first oscillator represents the existing building denoted by 1 as a subscript; on the contrary, the secondary one indicates the external structure that uses 2 as a subscript. In both cases, M_i K_i and C_i indicate mass stiffness and dumpling coefficients of the i-th oscillator, while $X_i(t)$ is its time displacement; the connection is considered to be non-dissipative with a Hooke spring whose stiffness is represented by coefficient K (Figure 1). Denoting relative displacements with U_i, the dynamic equilibrium derived from ground motion $X_g(t)$ is:

$$M_1\ddot{U}_1 + C_1\dot{U}_1 + K_1U_1 = -M_1\ddot{X}_g + K(U_2 - U_1) \quad (1)$$

with $U_1 = X_1 - X_g$, $U_2 = X_2 - X_g$ and ($\dot{}$) symbolising the derivative with respect to time t.
According to the suggested connection, the rigid coupling between the two oscillators represents the limit case of the Hooke spring in which stiffness coefficient tends to infinity (K → ∞). Therefore, $U_2 \to U_1$ and it is possible to verify the previous assumption of a Single-Degree-Of-Freedom (SDOF) system modifying Eq. (1) into the following one:

$$(M_1 + M_2)\ddot{U}_1 + (C_1 + C_2)\dot{U}_1 + (K_1 + K_2)U_1 = -(M_1 + M_2)\ddot{X}_g \tag{2}$$

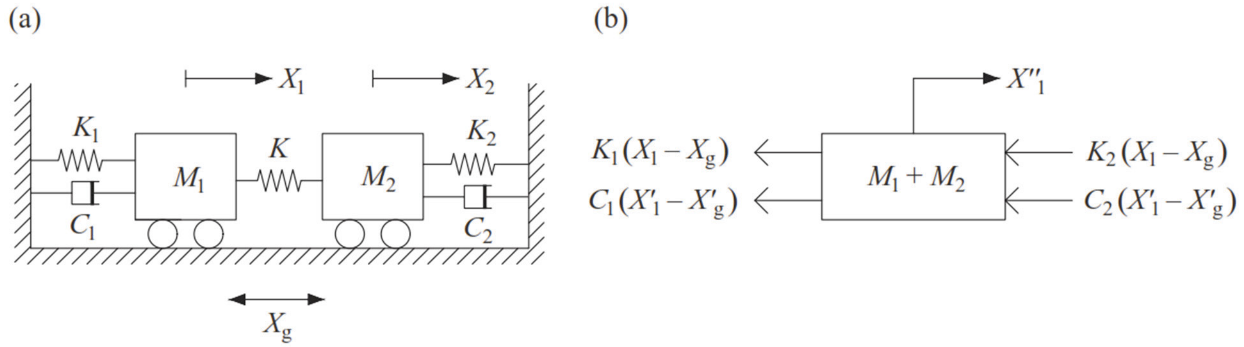

Fig. 1. Coupled system: (a) structural model; (b) free body diagram for a rigid coupling (K→∞)

3. Case study

On the back of the research analysed by Reggio et al. (2019), this chapter deals with the seismic response of an existing building (a multi-degree-of-freedom frame structure) and a real case study is shown to investigate how it behaves when a rigid connection links the former to an exoskeleton structure.
Two types of surveys have been pursued: a linear dynamic (also called modal) analysis has allowed to obtain maximum floor displacements, among all the results; stiffness data and steel statement have been acquired by a static non-linear analysis (also known as Push-Over).

3.1 Existing structure

The primary structure is part of the school complex named “De Amicis-Ruffini” which is located in Bordighera (in the province of Imperia, Italy). It is an isolated building composed by three stories over the basement, irregular floor plans and it reaches the dimensions of almost 75 m x 20 m (Fig. 2):

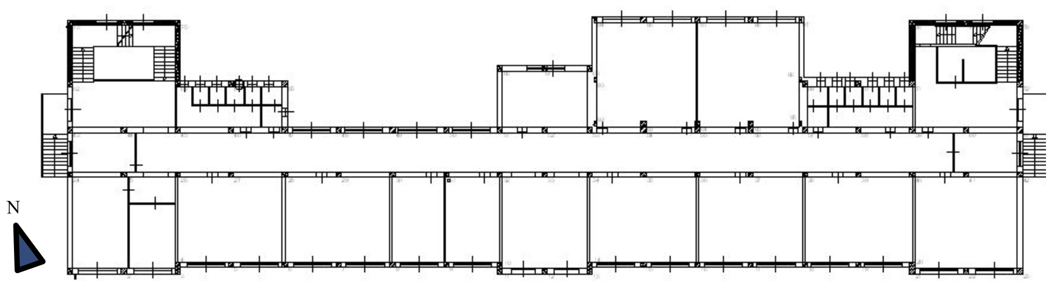

Fig. 2. Architectural plan of a standard floor

The construction dates back to the ’50s and it is a monodirectional reinforced concrete frame with lowered beams; vertical structural elements are arranged in regular interaxle spacings. Light concrete has been used for the slabs that

have a thickness of 24 cm.
The construction has preserved its original shape for decades until a new block has been introduced along the north side to enlarge the educational areas in the '80s. Its dimensions are reduced in comparison to those of the main building, being almost 16 m x 8,50 m, but it rises to the top level and its reinforced concrete frame only separate from the existing construction by means of a joint. Tests on no. 18 concrete specimens have been executed according to the Italian guideline on materials approved by CSLP (2017) and the resulting mean resistance to compression was $f_{cm} = 18{,}62\ MPa$. Then, foundations have been considered in XC2 category instead of XC1 for all the other elements in elevation, as reported in ENV 206 (2016) rule that indicates concrete characteristics necessary to classify atmospheric conditions that buildings have to bear. The last characterization concerns the subsoil, which has been described thanks to a geological inspection: it belongs to type B, i.e. "Soft rocks and sediments of coarse-grained highly thickened soils or fine-grained extremely compact soils", as defined in the Italian Building Code NTC (2018).
Consequently, a Finite Element (FE) model has been designed using the structural analysis software CDSWin (2019) with whom floor slabs have been intended to have an in-plane rigid behaviour. From now on, it can be also indicated with capital letter *U* that stands for "Uncoupled structure" to distinguish it from *C* of "Coupled system".

3.1.1 Safety assessment

Based on NTC (2018), the model of safety assessment related to this specific situation has been defined and justified. Starting from a historical-critical analysis and the building survey, mechanical characterisation of materials has followed and the level of knowledge applied was LC2; consequently, confidence factor is $FC = 1{,}20$. This numerical coefficient causes a reduction in material resistance that becomes equal to $f_{cm,red} = 16{,}85\ MPa$. At the end of the process, loads are taken into account and among them seismic actions are applied. It was possible to assume that the existing structure was not able to meet the requirements of current laws, as safety parameters were not assured: the majority part of structural elements did not validate shear verifications as well as combined compressive and bending stress tests.
Therefore, the solution to this serious issue is the innovative seismic adjustment called exoskeleton structure, as it has been defined so far. It allows to reach safety levels Italian Standards require, but it gives also the chance to retrofit the entire system following modern aesthetical and energetic aspects.

3.1.2 FE model

A reinforced concrete moment-resisting frame has been designed with non-ductile behaviour and uniform planar distribution of mass and stiffness. Floor slabs have an in-plane rigid performance, that has been validated thanks to slab thickness at least equal to 4 cm; indeed, Italian Building Code NTC (2018) explains that "as long as the available openings do not significantly reduce stiffness, horizontal stories may be considered infinitely rigid in their floor plan providing that they have been executed in reinforced concrete or in concrete masonry with at least a 40 mm-thick reinforced concrete slab […]".
Thus, each level has three degrees of freedom: two translations along x- and y-direction of the centre of gravity for every rigid floor and a rotation about z-axis. For the sake of simplicity, modelling does not concern non-structural elements.
The entire system includes the original building and the educational areas subsequently added; even if they are physically detached, the model has both of them because the separation joint does not guarantee free movement of the constructions in case of earthquake. This hypothesis should be considered during adjustment operations by means of adequate connections (e.g. shock transmitters) that can validate the assumption itself and prevent the risk of structural pounding. Figure 3 illustrates an axonometric view of the primary building, in which slabs have been hidden just to obtain a clearer graphical display.

3.2 Exoskeleton structure

Seismic adjustment has been carried on by the introduction of a self-supporting steel exoskeleton, which stands next to the existing construction but lying on its own rigid foundations. It rises from the planking level to the top on the entire façade and the structural elements it is made of are pillars, beams and diagonals; they all are S275 steels except for Φ120 bracings, that have been designed with S235 type for constructive requirements.

Columns cross-sections change depending on their position:

- HEB300 section bars are used at east-west ends of the main façades, on either side of the entrance staircase and all around the new stairwell/elevator shaft;
- HEA200 structural steels have been introduced in any other case.

Taking about beams, they are arranged as follows:

- HEA180 bars belong to the frame;
- HEA100 sections for connections between the existing structure and the external one; they are placed at each floor like rigid links.

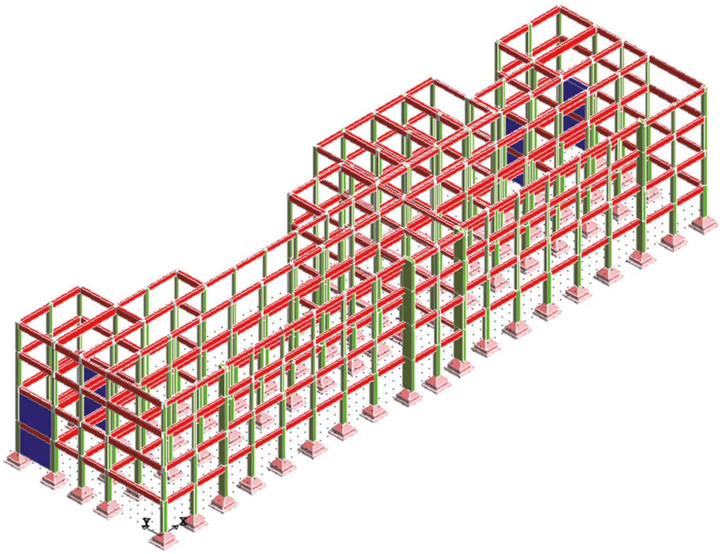

Fig. 3. FE model of the existing structure

Dealing now with cross-shaped bracings, three different solid section rods appear:

- Φ120 types have been introduced on x-z plane like reinforced elements for stairwells, to cover the spans between HEB300 pillars of north and south facades, on y-z plane along the short sides of the building and sometimes on the north façade as a way to stiffen along y-direction where needed;
- Φ50 bars have been placed on vertical x-z and y-z planes to transfer seismic actions at nodes from the existing floors to the exoskeleton aiming at avoiding the onset of bending moments; they are also on horizontal x-y plane.

Each node of the exoskeleton has been located outside of the existing floors no matter was the level, in order to let the two structures work separately towards the same goal. Exoskeleton pillars have fixed supports at the base, corresponding to 2.30 m, i.e. the level from which primary building raises. Moreover, in the interests of safety, analysis have been executed setting up a minimum vulnerability index equal to $\zeta_E = 100\%$, as to assure the highest level of adjustment Italian Standard NTC (2018) grants.

The final axonometric view of the retrofitted system emerges in Figure 4.

It can be noticed that the introduction of the exoskeleton has enabled to make a more regular floor plan (Figure 5), unlike it was before. In fact, despite observing distance limitations between adjacent buildings as reported in Interdepartmental Ordinance no.1444 (1968), a rectangular perimeter has been created wherever possible.

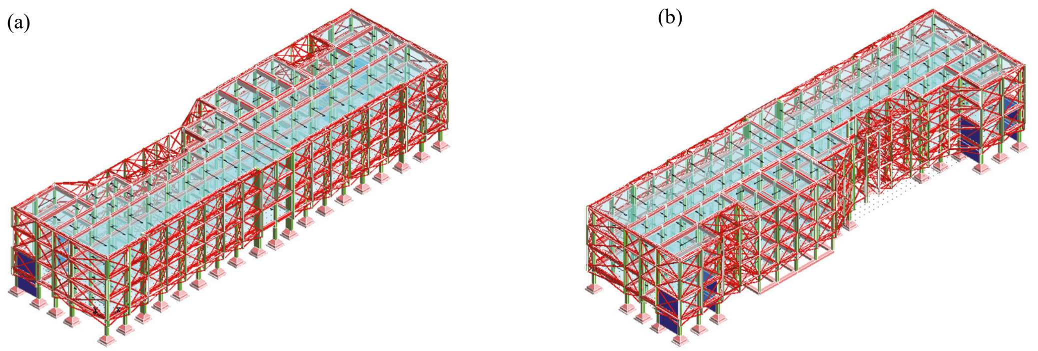

Fig. 4. Axonometric views of the retrofitted system: (a) south side; (b) north side

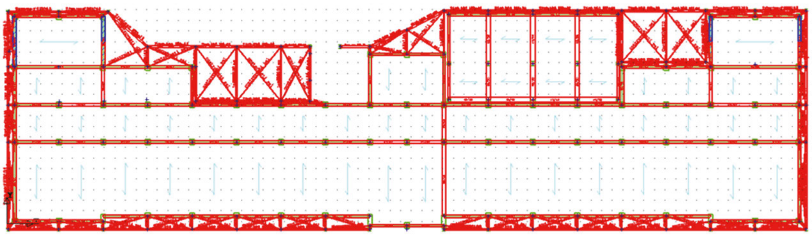

Fig. 5. First floor of the retrofitted system

3.3 Modal properties and seismic analyses

The following table, Table 1, shows the comparison between modal properties of the primary construction and those of the coupled system. Lacking symmetry, rotational modes are involved in modal analysis with considerable participating mass ratios.

Table 1. Modal properties of the primary structure and the coupled system: circular frequencies Ω, periods T, participating mass ratios M_x and M_y in x- and y-direction respectively

	Primary structure				Coupled system			
Mode	Ω [rad/s]	T [s]	M_x [%]	M_y [%]	Ω [rad/s]	T [s]	M_x [%]	M_y [%]
1	8.119	0.774	0.03	74.92	21.483	0.292	0.05	71.99
2	9.213	0.682	14.64	3.89	26.364	0.238	77.35	0.05
3	9.569	0.657	66.85	0.58	31.035	0.202	0.13	0.02
4	21.247	0.296	0.02	9.05	53.536	0.117	0.02	19.68
5	23.656	0.266	0.02	7.53	57.922	0.108	14.88	0.04
6	25.519	0.246	14.27	0.00	65.321	0.096	0.07	0.59
7	42.349	0.148	1.93	0.00	75.869	0.083	3.52	0.03
8	43.707	0.144	0.11	0.12	78.785	0.080	0.09	3.36
9	47.536	0.132	0.00	1.82	86.378	0.073	0.00	0.43
10	56.716	0.111	2.13	0.00	86.939	0.072	3.89	0.02
11	78.745	0.080	0.00	2.08	113.130	0.056	0.00	3.73
12	88.707	0.071	0.00	0.00	129.367	0.049	0.01	0.05

The coupled system has clearly higher frequencies than the existing building because of the increase in stiffness due to the steel exoskeleton, as it is defined in Section 3.4. Just focusing on the main three modes, the first one goes through a rise of 164% in frequency and the period almost reduces to one-third; frequency of the second translational

mode upsurges of 186% and period drops from 0.682 s to 0.238 s; rotational mode is relevant while considering the existing irregular building, but it nearly cancels when the exoskeleton is introduced, as it can be checked from mass ratios values. So, it highlights that the external structure has reached the greatest possible planar regularity.
Seismic analyses of the two FE models (the primary structure and the coupled system) have been run aiming at understanding the behaviour of each one due to the action of earthquake forces. The input is described by pseudo-acceleration response spectra that agree with the Italian Building Code, NTC (2018), and the results drew attention on Damage and Life-safety Limit States; the first one is characterized by a peak ground acceleration $a_g = 0.036g$ with 63% of exceedance probability in 50 years, while LLS refers to a probability of exceedance equal to 10% in 50 years and its peak ground acceleration is $a_g = 0.130g$. These data have been acquired from the Institutional technical agency CSLP (2019) in accordance with national regulation NTC (2018).

3.4 Seismic response

Dynamic analysis has allowed to discover seismic response characteristics like maximum floor displacements, inter-storey drifts and shear forces; they are the main useful quantities to control the behaviour of a structure from a seismic and vulnerability point of view.
Peak floor displacements and inter-storey drift ratios are reported in Table 2 and 3, in which Damage and Life-safety Limit States (DLS and LLS) have been considered for the existing structure and the combined primary-exoskeleton system.

Table 2. Peak floor displacements (U_x, U_y) and inter-storey drift ratios (Δ_x, Δ_y) in x- and y-directions for the primary structure and the coupled system, DLS

	Primary structure				Coupled system			
Level	U_x [m]	U_y [m]	Δ_x [‰]	Δ_y [‰]	U_x [m]	U_y [m]	Δ_x [‰]	Δ_y [‰]
1	0.005	0.005	1.3	1.4	0.001	0.001	0.2	0.3
2	0.008	0.008	0.9	0.8	0.001	0.002	0.2	0.2
3	0.014	0.015	1.6	1.7	0.002	0.003	0.2	0.3
4	0.018	0.020	1.2	1.6	0.003	0.004	0.2	0.3

In Section 7.3.6.1/part (a) the Italian Building Code, NTC (2018), demands a stiffness verification of CU II-type constructions for DLS in which inter-storey drift ratios must be less than or equal to $0.005\ h_i$, where h_i stands for each floor height. The original construction has different inter-storey elevations which vary from $3.55\ m$ to $3.83\ m$, but maximum value $d_{max} = 0.005\ h_i = 0.02\ m$ remains the same. Therefore, Figure 6 illustrates the profiles of inter-storey drift ratios for the two constructions, i.e. the existing building (U) and the coupled system (C).

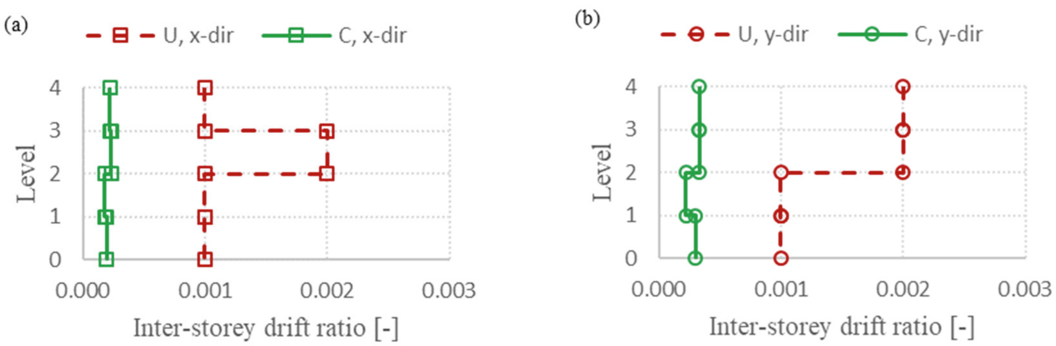

Fig. 6. Inter-storey drift ratios for the primary structure and the coupled system, DLS: (a) x-direction; (b) y-direction

In both cases, values are fully less than $dU_i/h_i = 0.005$ so verifications have been validated (dU_i indicates the

difference in floor displacement). In fact, the ratio of the primary structure fluctuates from a third and one-fifth less than the limit while the ratio referred to the coupled system is at most a twentieth of 5‰.
Data concerning Life-safety LS are shown below:

Table 3. Peak floor displacements (U_x, U_y) in x- and y-directions for the primary structure and the coupled system, LLS

	Primary structure		Coupled system	
Level	U_x [m]	U_y [m]	U_x [m]	U_y [m]
1	0.012	0.013	0.001	0.002
2	0.021	0.021	0.003	0.004
3	0.037	0.038	0.005	0.007
4	0.048	0.053	0.006	0.009

Floor displacements are clearly higher than those of Damage LS, but they show promising results: the coupled system still preserves minimal values reaching, at the top, just a maximum of almost 6 mm in x-direction and 9 mm in y-direction, due to its lower stiffness. Along x-direction, the retrofitted structure achieves a huge reduction in displacements at the top level passing from 0.048 m to 0.006 m, thus it is equal to -87.50%; in the transverse (y) direction, it decreases of 83%. Concerning trends are illustrated in Figure 7.

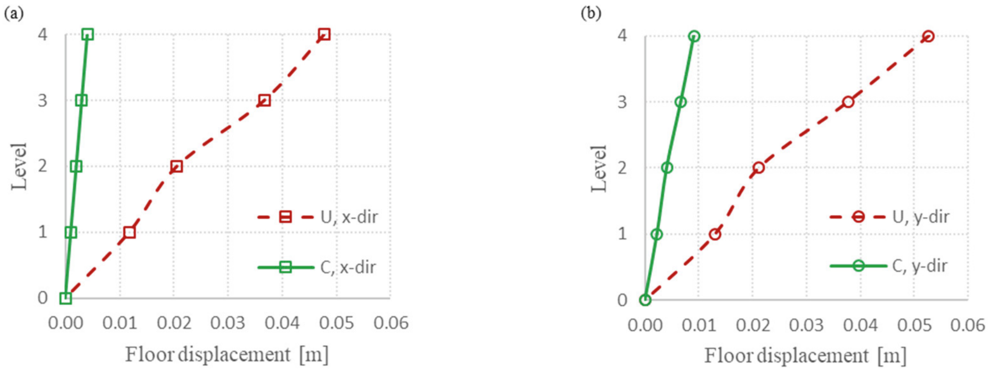

Fig. 7. Profiles of floor displacements for the primary structure and the coupled system, LLS: (a) x-direction; (b) y-direction

Another subject to tackle is the stiffness of the two structures, whose values have been derived from Push-Over analysis. The Italian Building Code, NTC (2018), declares that seismic actions must be applied according to the combinations $\pm F_x \pm 0{,}30\, F_y \pm \xi$ and $\pm F_y \pm 0{,}30\, F_x \pm \xi$ where $\xi = 5\%$ represents the viscous damping. Sizes of the structural elements for the exoskeleton considered two aspects: stiffness ratio between the retrofitted system and the existing building, but also planar regularisation in order to minimise the eccentricity that is created between the gravity centre and stiffness centre so as to reduce torsional effects due to earthquake actions. In fact, the standards NTC (2018) literally express that "under horizontal actions, full contribution to stiffness and to resistance of the secondary elements cannot exceed 15% of the same contribution of primary elements". Thus, for the present study, it means that the stiffness of the coupled system must be at least 85% of the total; in other words, stiffness ratio must overtake 6.66; Table 4 reveals two examples with the relating positive results.
In addition to the previous outcomes, interesting reductions in terms of internal forces of the existing building have been found due to the established rigid connection for Life-safety LS: peak shear forces (V_x, V_y) referred to the primary construction and the coupled system are shown in Table 5, while base shears (V_b) for every structure along each direction are reported in Table 6.
In general, the introduction of the external structure causes an increase in reactions because mass, stiffness and frequencies have grown. Nevertheless, from here on the coupling starts working since the forces merely acting to the primary structure are significantly reduced compared to the existing construction: contributions of the primary

structure, the existing one forming part of the coupled system and the only exoskeleton structure have been split in order to clearly understand the effectiveness of the investigated solution, as reported also in Figure 8.

Table 4. Stiffness of the primary structure (k_{prim}) and the coupled system (k_{syst}) for two seismic combinations and their stiffness ratio

	Primary structure	Coupled system	Ratio
Direction	k_{prim} [t/m]	k_{syst} [t/m]	k_{syst} / k_{prim} [-]
$F_x + 0.30\, F_y + \xi$	24514	171919	7.01
$F_y - 0.30\, F_x - \xi$	16453	112320	6.83

Table 5. Peak shear forces (V_x, V_y) for the primary structure and the coupled system in x- and y-direction, LLS

	Primary structure		Coupled system	
Level	V_x [kN]	V_y [kN]	V_x [kN]	V_y [kN]
1	6428.80	6114.20	12841.50	11915.10
2	5676.70	5378.30	11776.60	11009.70
3	4189.70	4078.50	8962.80	8861.10
4	1913.50	1980.60	4593.50	4808.60

Table 6. Base shear forces (V_b) for the existing structure and the primary-exoskeleton components of the coupled system in x- and y-direction, LLS

	Primary structure		Coupled system		
V_b $[kN]$		Total	Primary	Exoskeleton	Total
x-dir	6428.80	6428.80	1729.00	11112.50	12841.50
y-dir	6114.20	6114.20	1655.00	10260.10	11915.10

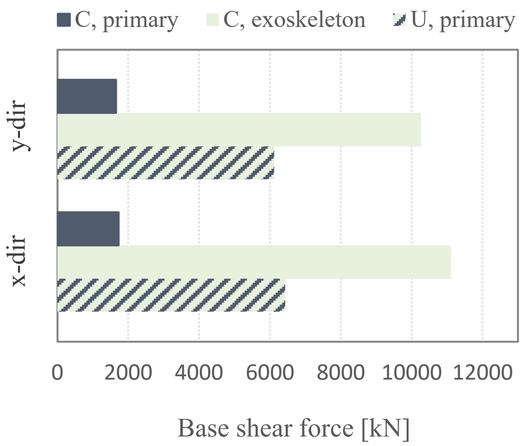

Fig. 8. Comparison between base shear forces of the existing structure and the primary-exoskeleton components of the coupled system in x- and y-direction, LLS

The previous figure shows that total base shear increases from $6114.20\ kN$ to $10260.10 + 1655.00 = 11915.10\ kN$ in y-direction and from $6428.80\ kN$ to $11112.50 + 1729.00 = 12841.50\ kN$ in longitudinal (x) direction. Anyway, it is necessary to highlight an evident reduction in shear force for the existing component of the coupled system that goes from $6114.20\ kN$ to $1655.00\ kN$ in y-direction and from $6428.80\ kN$ to $1729.00\ kN$ in x-direction, which means it is more than three times lower. Thus, the primary building just gets almost a quarter of the seismic actions than it currently happens. Briefly, equivalent seismic force increases when the external structure is introduced because this higher stiffness causes a raise in acceleration and a reduction in period of vibration, as it is reported in Table 1. However, the exoskeleton manages to unload the primary building from total shear force of a considerable amount ascribing the major part to itself; this behaviour comes from the incorporation of compressive forces made by the exoskeleton that turns them into horizontal components. To be exact, more than 86% of base shear force refers to the external structure along each direction, as may be noticed in Table 6.
Finally, Table 7 indicates all the steel sections that have been employed to build the exoskeleton classifying them according to some specific data like the structural element that uses them, the type of material, unit and total areas, total lengths and their mass.

Table 7. Steel statement of the exoskeleton structure

Section	Structural element	Steel	Unit area [cm²]	Total area [m²]	Total lenght [m]	Mass [kg]
HEB 200	column	s275	53.83	462.77	407.37	17214.37
HEB 300	column	s275	149.08	432.75	250	29256.56
HEA 100	link	s275	21.23	132.76	238.94	3982.07
HEA 180	beam	s275	43.51	936.47	921.27	31467.02
Φ50	vertical bracing	s275	19.63	356.34	2269.67	34983.42
Φ120	vertical bracing	s235	113.10	373.08	992.25	88093.35
Φ50	horizontal bracing	s275	19.63	227.63	1824.98	28129.22
Total						233126.01

Considering the price of the steel equal to $4\ €/kg$ inclusive of material and working tasks, the total amount of money stands at $932{,}504$ € that corresponds to $155.42\ €/m^2$. This is an encouraging result with respect to the estimated cost of almost $800\ €/m^2$ for a traditional adjustment of an existing building.

4. Conclusions

This research was focused on exploring if an exoskeleton structure could represent an effective solution to seismic adjustment of a real existing building and what response it could exhibit.
The idea allowed to create a dynamic system whose design could be adapted to the needs basing on the primary structure it is rigidly linked to. Then, seismic analyses have been performed and relating results between the original structure and the retrofitted system are:

- a floor displacements reduction at most by 80% for both Damage and Life-safety Limit States;
- a growth of frequencies, higher than 160%, because of an increase in mass and stiffness;
- despite of lower periods of vibration for the coupled system, shear forces in the primary building turned three times smaller and the final configuration showed that more than 86% of them have been taken only by the exoskeleton;
- a more effective behaviour along x-direction, because it is stiffer than the transverse (y) one;
- cost of operations is fully lower than the price required by a standard adjustment;
- preservation of the existing building that avoids both demolition and heavy reconstruction works, thanks to external operations which consist of adding a new steel frame able to embrace and rigidly connect it;
- the overall dimensions of this solution are nearly limited to the perimeter of the primary construction, given that it just needs a practical distance to put the exoskeleton foundations beyond the existing ones; thus, it

represents a useful answer to isolated urban structures that are no longer in compliance with the current standards.

As a result, the exoskeleton structure can be judged a method capable of coping with the problem of seismic adjustment of existing constructions even giving them the chance to gain new energetic and aesthetic features.

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