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Retrofit of Existing Reinforced Concrete (RC) Buildings: Steel vs. RC Exoskeletons

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Abstract: The existing building stock is largely made up of reinforced concrete (RC) buildings, constructed between the post-World War II period and 1981, and mostly consists of buildings constructed very quickly to meet the great housing demand of this period, and buildings that do not adhere to anti-seismic and energy regulations. Today, after more than fifty years, these buildings have reached the end of their useful life cycle and their maintenance is not sustainable, presenting a series of structural, energy and architectural problems and criticalities. The myriad of possible retrofit interventions currently available for these RC structures drastically reduces when the main requirement for interventions is to avoid operational interruptions to buildings. In this case, an additive structure, operating exclusively from the outside as an exoskeleton, is typically used for achieving appropriate retrofit. In this paper, two solutions are proposed and addressed for the retrofit of an existing RC building in Italy, one through the application of a steel exoskeleton and the other through the application of an RC exoskeleton system. A set of push-over (PO) analyses is carried out to define the performance point of both the original and combined systems. The comparative results of these solutions are then discussed.

Keywords: sustainable and reversible repair; reinforced concrete (RC); steel; exoskeleton; existing buildings

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1. Introduction

Continuous experimentation and research in the field of architecture and engineering have led to important results in terms of requirements and technical skills. Today, many of the buildings constructed since the Second World War are in a critical situation, as they are not sustainable [1–3]; they do not meet various contemporary standards, both in terms of living comfort and energy; and above all, from a structural point of view, these buildings often do not meet modern safety requirements with respect to vertical load [4], and are not designed to accommodate seismic action.

Most of these buildings have reached the end of their useful life (50 years) according to Italian standard requirements [5]. It is thus evident that a dramatic situation emerges, in which entire housing sectors are highly obsolete and vulnerable, and very often located within highly degraded urban contexts. There is a clear need for action to address the performance and structural deficiencies of post-World War II buildings and to reduce the current unsustainable energy waste through requalification operations [6].

The retrofit of such buildings is a solution that aims to adapt past constructions to contemporary levels and standards, while at the same time ensuring that these interventions produce important results in the structural, energy and architectural fields, without neglecting the urban context in which they are located [7].

With the spread of the theme of sustainable redevelopment combined with that of energy saving [8–10], research has been directed towards high-performance and effective solutions. These no longer involve the classic demolition and reconstruction of obsolete and vulnerable buildings, but promote their valorisation through reversible and more economically advantageous interventions. This produces a series of advantages in economic terms, but also from the point of view of finding useful raw materials for new construction and the disposal of rubble resulting from demolition [11–13]. Today, there are a myriad of interventions available for the retrofit of such buildings [14–17]. However, the number and type of these possible interventions are drastically reduced when the most important requirement is to avoid interruption to the operation of buildings under intervention. Reference is thus made to an innovative solution which first appeared on Russian soil in the late 1800s and early 1900s, when Vladimir Shukhov developed a self-supporting structural system [18].

This type of intervention, well known as an "exoskeleton", consists of an additive strategy in which the existing building is wrapped in a steel or reinforced concrete (RC) framework that is rigidly connected to the primary structure, thus effectively modifying the dynamic response of the system and remedying the vulnerabilities typical of this type of building [19–22].

The present work is part of an extended research project aimed at developing a holistic retrofit intervention strategy for existing RC buildings, so that—through a multidisciplinary approach—the problem can be addressed in unified way to achieve adequate levels of structural safety, liveability and functionality. In more detail, this research project aims to study, in addition to the effects of exoskeleton systems, the effects of their connection systems, as well as the possible improvements (from both energetic and seismic points of view) to the infill walls.

To improve the energy aspects of these types of buildings, and at the same time the seismic-related aspects, the use of natural materials such as cork and basalt fibre is envisaged. There are, in fact, plans to apply natural thermo-plaster with fibre composite matrices along the perimeter walls of these buildings to achieve a beneficial dual effect for energy and seismic issues. From the energy point of view, such an intervention would make it possible to reduce consumption and even achieve performance levels close to nZEB (nearly zero-energy building). From the seismic point of view, premature collapse would be prevented. To this end, two experimental campaigns were recently launched: (i) the study of connection systems with the existing structure and exoskeletons (i.e., dissipation devices in place of rigid links), and (ii) characterising the basic materials and then the composite system.

For combined seismic consolidation and improving the energy efficiency of the infill walls, the experimental program in progress includes mechanical bending and compression tests on lime mortar matrices, tensile tests on fibres of vegetable materials, and additional thermal conductivity tests on cork panels. The results will be further discussed in the subsequent project stages. Most importantly, this intervention strategy, based on the integration of different disciplines and technologies, can allow for a multi-benefit approach capable of achieving high standards in existing buildings, not only in terms of seismic safety, but also in the form of socio-economic sustainability and energy requirements [23–25]. In addition, it also increases the real estate value of existing buildings and extends their life cycle, following the classical criteria of sustainability and the velocity of realization.

In this context, this paper presents two preliminary applications of exoskeletons (one constructed in steel and one in RC) for a typical case study residential building built in the 1970s. The comparative numerical results are discussed in terms of structural and constructional efficiency, and represent the basis of further retrofit and enhancement interventions.

2. Case Study Building

The examined case study system is an RC building located in the Municipality of Reggio Calabria (RC), Italy, near the Mediterranean University of Reggio Calabria (Figure 1). The system consists of a residential building with a multi-story RC frame structure and brick infill, built in the early 1970s, as documented by calculation reports found in accessible historical archives.

Figure 1. Localization and general view of the case study RC building in Reggio Calabria (Italy).

The building structure was originally designed in accordance with the Technical Standards of Royal Decree N. 2229 of 16 November 1939, which presents "Standards for the execution of simple and reinforced concrete structures" [26,27]. The structural solution is typical of buildings constructed in the 1970s, and resistant only to gravity loads. The case study system has a typical L-shaped plan layout, with maximum dimensions of 28.0 m × 22.0 m (Figure 2).

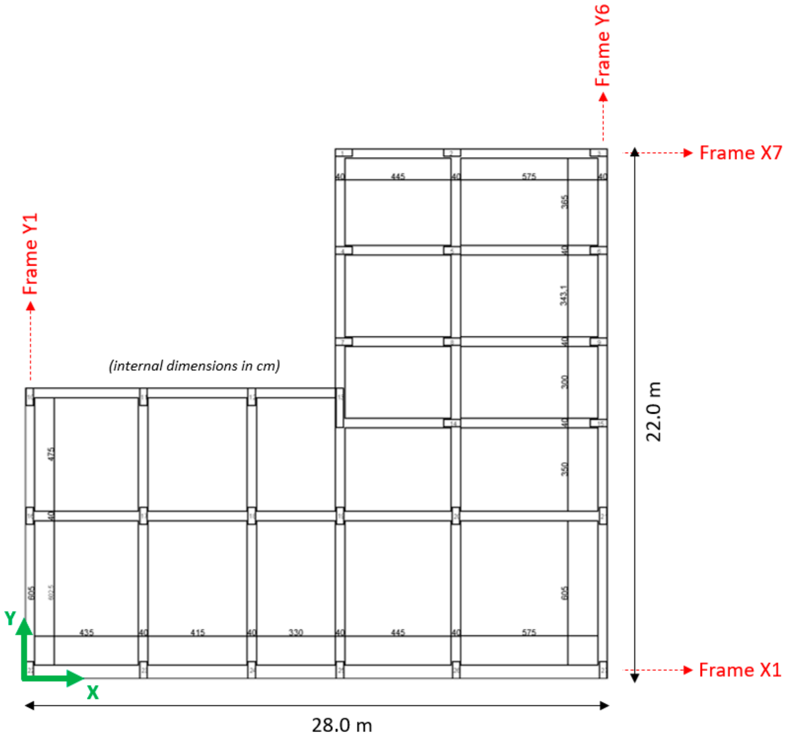
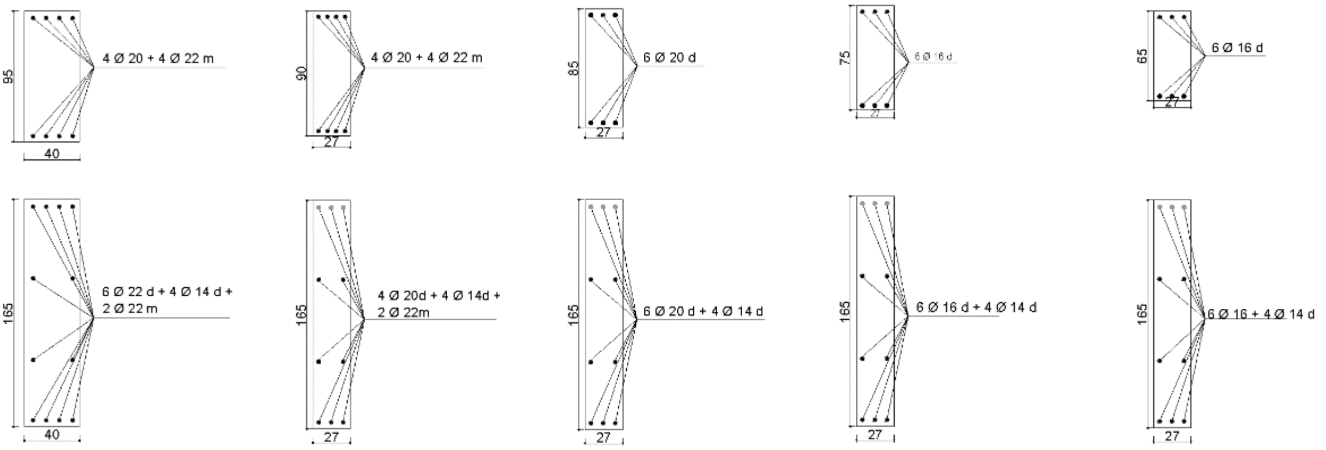


Figure 2. Typical horizontal section of the 1st floor (scanned archive drawings).

The system is also characterized by seven moment-resisting frames arranged along the X-direction and six moment-resisting frames arranged along the Y-direction. These assembled frames comprise the 3D-resistant structure. In the elevation, the building consists of six floors; the first story level has a total height of 3.6 m, while the inter-floor height of the other five floors is reduced to 3.4 m.

Knowledge of the basic structural characteristics of the building components was obtained by a campaign of diagnostic investigations, including non-destructive (pacometric and rebound hammer tests) and destructive (compressive tests on cores and tension tests on steel) experiments. In accordance with NTC2018 [28], the level of the building regarding geometry, structural details and material properties is to be considered equal to level 2 (LC2).

The foundations are superficial and consist of orthogonal RC beams. All the RC beams and columns for the 3D system, as shown in Figure 2, have a rectangular cross-section, with dimensions summarized in Figure 3.



Ground level 1st 2nd 3rd 4th

Figure 3. Geometrical properties of beams and columns for the building construction grouped by story level (scanned archive drawings). Section dimensions are given in cm.

The concrete resistance class originally used in the construction of the building was R_{bk} 250. For the mechanical characterization of concrete, a number of 26 cores were extracted from selected structural elements. To this end, two cores were taken for beams and columns at the level of each floor, with the addition of two cores for the foundation beams. Based on major information and the details herein summarized, it was possible to obtain the previously amended knowledge level LC2 for structural analysis. An average strength value of 15 MPa, as obtained from the material characterization tests, was in fact used in the current numerical simulations. The steel shear reinforcement for RC beams consisted of ϕ6 transverse stirrup smooth rebars with 150 mm spacing, while the transverse stirrups of RC columns were realized with ϕ6 members, with spacing between 200 mm and 300 mm. The type of used steel was Aq50, with a minimum yield strength of 270 MPa. In the present numerical analyses, according to Verderame [29], a reference value of 372 MPa was taken into account.

2.1. Analysis of Bare RC Building

The case study building has been in a state of decay and neglected for several years, today presenting a series of serious problems and criticalities in terms of obsolescence and vulnerability (see Figure 4).

From a structural point of view, while withstanding vertical actions (NTC2018), the building is in fact not able to withstand horizontal seismic action. Moreover, its useful life cycle (50 years) has expired.


(**a**) (**b**)

Figure 4. State of the case study RC building: (**a**) external view and (**b**) example of internal view.

In order to assess the current seismic performance for the RC building under study, a push-over (PO) analysis was thus carried out by taking advantage of the distributed plasticity approach models according to the N2 method [30–33]. More precisely, the reference numerical models were developed using commercial finite element software [34], considering the combination of seismic components acting simultaneously in the X- and Y-directions. In doing so, moreover, two typical load distributions were considered in the elevation of the 3D system, namely, a set of monotonically increasing lateral forces:

- Proportional to the first vibration shape of the bare RC frame system;
- Proportional to the distribution of masses.

Figure 5 shows the typical PO curve for the bare RC frame with the corresponding bilinear equivalent curve at the life safety limit state (SLV) for the existing building.

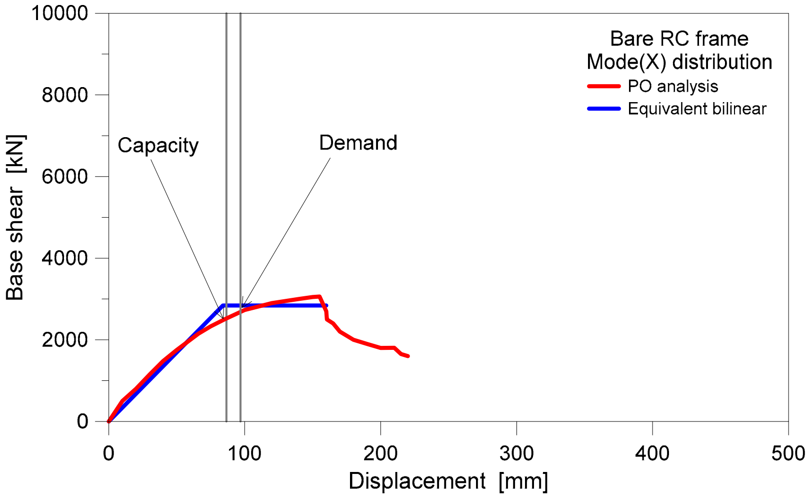


Figure 5. Results of PO analysis for the bare RC building in the pre-intervention stage, overlooking the accidental eccentricity of seismic lateral forces.

Figure 5 disregards the combination of seismic components. In particular, the results of the PO analysis were carried out in the positive X-direction for load distribution, proportional to the first vibration mode shape, neglecting the combinations of seismic components. It can be observed how the capacity "*C*" (up to 86.5 mm of displacement) is significantly lower than demand "*D*" (in the order of 96.9 mm, that is, 11%).

Figure 6 shows the calculated PO curve with the corresponding bilinear curve at the SLV for the existing building, considering the combinations of seismic components, which were conventionally taken into account as [5,35]:

$$\pm(X) \pm 0.3(Y) \tag{1}$$

$$\pm(Y) \pm 0.3(X) \tag{2}$$

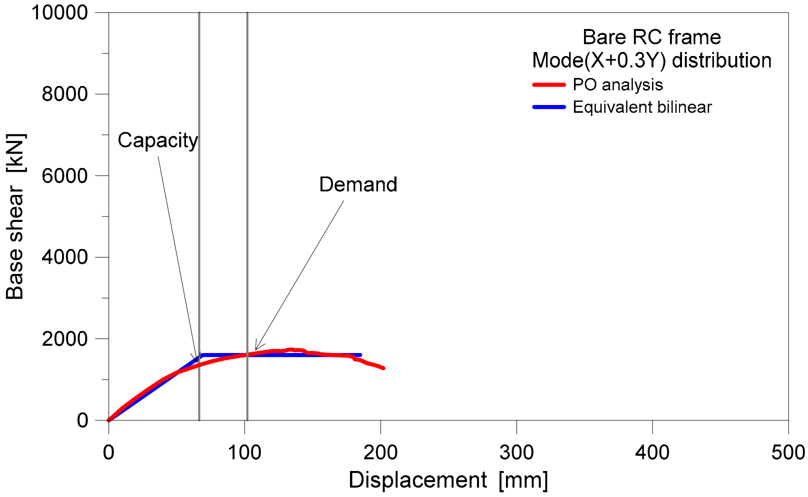


Figure 6. Results of PO analysis for the bare RC building in the pre-intervention stage, considering the combination of seismic components acting simultaneously in X- and Y-directions.

The comparative numerical results, in terms of capacity and demand of the system, are reported in Table 1. In this case, only a critical situation is found, which corresponds to the PO analysis carried out in the positive X-direction for load distribution proportional to the first vibration mode shape.

Table 1. Results of PO analysis for the bare RC building in the pre-intervention stage, overlooking the combinations of the seismic components.

Push-Over	F_{max} (kN)	Γ	F^*_{max} (kN)	α_u/α_1	$S_e(T^*)$ (g)	q_*	C (cm)	D (cm)	S
Mode (+*X*)	3785	1.49	2536	0.961	0.334	1.2	8.65	9.69	0.89
Mode (−*X*)	3771	1.49	2526	1.06	0.336	1.3	10.82	9.64	1.12
Mode (+*Y*)	4749	1.43	3319	0.968	0.361	1.2	10.64	8.97	1.18
Mode (−*Y*)	4913	1.43	3434	0.999	0.352	1.2	11.20	9.21	1.21
Mass (+X)	6307	1.49	4226	0.793	0.398	1.0	11.38	8.15	1.39
Mass (−*X*)	6136	1.49	4111	1.49	0.40	1.0	8.34	8.10	1.03
Mass (+*Y*)	7547	1.43	5275	1.75	0.437	1.0	12.64	7.41	1.70
Mass (−*Y*)	7548	1.43	5276	1.55	0.428	1.0	12.06	7.56	1.59

F_{max}: Maximum value of horizontal force applied on the structure (base shear); Γ: participation coefficient; $F_{max}{}^* = F_{max}/\Gamma$; α_u/α_1: ratio between the value of the seismic action for which the formation of a number of plastic hinges occurs such that the structure becomes labile, and that for which the first structural element reaches plasticity; $S_e(T^*)$: elastic response spectrum corresponding to period T^*; q^*: behaviour factor ($q^* = m^* S_e(T^*)/F_y{}^*$); C: displacement capacity of the structure; *D*: displacement demand for the control point of the structure; $S = C/D$: safety index.

In Table 2, detailed results from the PO analyses considering the combination of seismic components, as indicated in Equations (1) and (2), are also presented. As it is easy to verify, in this case, the calculated C/D ratio is less than the unity value for ten out of the sixteen examined cases (≈0.63%), hence denoting the critical conditions of the system in its state of configuration.

Table 2. Results of PO analysis for the bare RC building in the pre-intervention stage, considering the combination of seismic components.

Push-Over	F_{max} (kN)	Γ	F^*_{max} (kN)	α_u/α_1	$S_e(T^*)$ (g)	q_*	C (cm)	D (cm)	S
Mode $+X+0.3Y$	2317	1.60	1447	1.37	0.309	1.8	5.86	10.49	0.56
Mode $+X-0.3Y$	3202	1.60	2001	2.09	0.348	1.4	5.61	9.31	0.60
Mode $-X+0.3Y$	3210	1.60	2005	2.05	0.346	1.4	7.01	9.36	0.75
Mode $-X-0.3Y$	2326	1.60	1453	1.50	0.306	1.8	7.11	10.59	0.67
Mode $+Y+0.3X$	2837	1.51	1880	1.00	0.323	1.8	8.19	10.03	0.82
Mode $+Y-0.3X$	5408	1.51	3584	1.65	0.423	1.2	9.64	7.67	1.26
Mode $-Y+0.3X$	5852	1.51	3878	1.61	0.418	1.1	9.18	7.75	1.18
Mode $-Y-0.3X$	2895	1.51	1918	1.14	0.324	1.8	8.03	10.01	0.80
Mass $+X+0.3Y$	4836	1.60	3022	1.87	0.409	1.1	8.09	8.11	0.99
Mass $+X-0.3Y$	4887	1.60	3054	1.94	0.409	1.1	7.84	7.92	0.99
Mass $-X+0.3Y$	4918	1.60	3073	1.90	0.409	1.1	6.61	7.93	0.84
Mass $-X-0.3Y$	4725	1.60	2952	1.95	0.409	1.1	7.99	8.10	0.99
Mass $+Y+0.3X$	6439	1.51	4267	1.63	0.435	1.1	11.12	7.45	1.49
Mass $+Y-0.3X$	7000	1.51	4639	1.37	0.477	1.1	10.25	6.79	1.51
Mass $-Y+0.3X$	7373	1.51	4886	1.32	0.469	1.0	12.00	6.90	1.74
Mass $-Y-0.3X$	6659	1.51	4413	1.71	0.430	1.0	8.69	7.53	1.15

2.2. Retrofit Strategy for the Existing Building

Generally, for the retrofit of existing RC buildings, two different intervention strategies aimed at improving structural safety indices can be efficiently developed. These strategies include (i) increasing displacement capacity or (ii) reducing displacement demand [23,31].

In this contribution, the retrofit strategy was focused on reducing the earthquake-induced displacement demand within the capacity limits of the existing structure through the application of two types of exoskeletons, one composed of steel and one of RC. In detail, both the steel and RC exoskeleton systems were designed to reduce the seismic demand of the existing structure to a minimum.

It is important to point out that the two solutions compared to each other in this paper were actually proposed by the Technical Office of the University.

The architects contemplated:

- From an energy point of view, the elimination of thermal bridges and the renewal of outdated technological systems;
- From an architectural point of view, the conferment of a greater architectural value and a better distribution of accommodation that meets current housing standards;
- From a structural point of view, improvement in the seismic capacity of the original RC building.

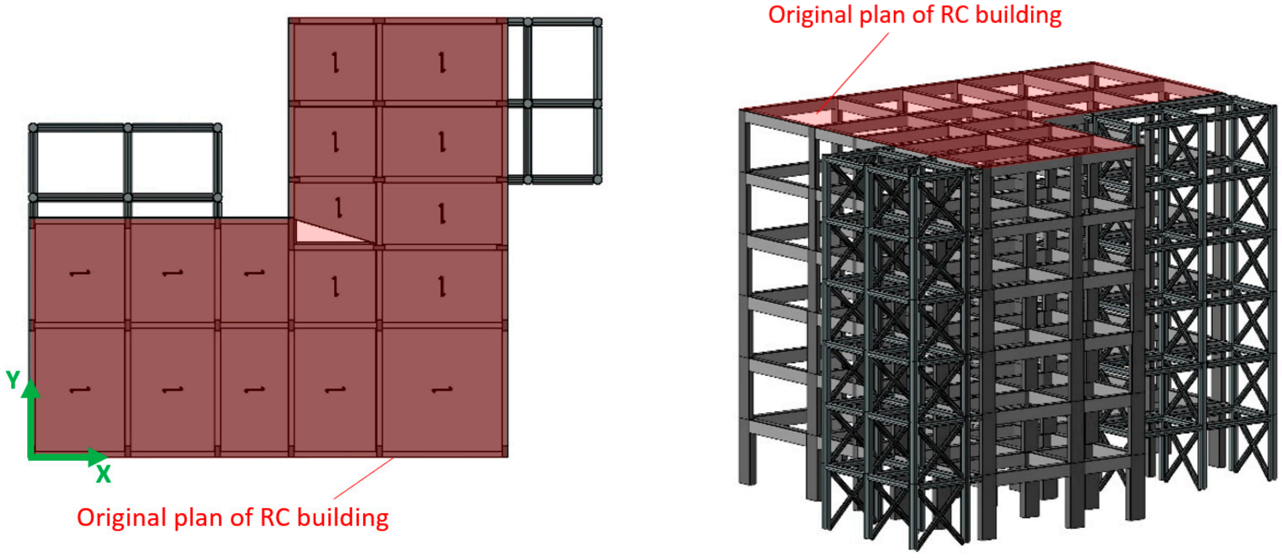
In light of these objectives, two alternative solutions of retrofitting were specifically studied, namely:

- The construction of a steel exoskeleton to make evident and keep clear the difference between the existing RC building and the new constructional system for retrofit;
- A second option envisaging the construction of new RC frames in continuity with the existing structure, so as to minimize and possibly hide the differences between the existing RC building and the new retrofitted parts.

2.3. Application of Steel Exoskeleton

At first, a steel exoskeleton, as shown in Figure 7, was taken into account. As shown, the exoskeleton layout is intended to cover part of the east elevation of the existing building, as well as part of the west elevation side. Structurally speaking, the steel exoskeleton consists of a frame with tubular bracing which is connected to the existing RC frame by rigid links. In more detail, the steel exoskeleton is designed with:

- Columns for the first, second, and third floors—CHS 457 × 40;
- A column for the fourth floor—CHS 457 × 32;
- Columns for the fifth and sixth floors—CHS 457 × 20;
- Beams—CHS 406 × 16;
- Concentric bracing—CHS 273 × 16;
- Rigid links to locally connect the external exoskeleton with the existing RC building.



(**a**) (**b**)

Figure 7. Retrofit intervention for the bare RC building with steel exoskeleton: (**a**) plan and (**b**) axonometric views. The original layout of the RC building and the newly added steel structure.

In order to assess the performance of the RC building with the steel exoskeleton, PO analyses were performed with typical results, as shown in Figure 8 and Table 3.

From Figure 8, it can be noted that the retrofit intervention produces a series of effects, namely: (i) an increase in the overall lateral stiffness of the bare RC building; (ii) an improvement in the seismic safety index; and (iii) a marked increase in capacity, also due to the reduction in eccentricity between the centre of mass (CM) and the centre of stiffness (CS).

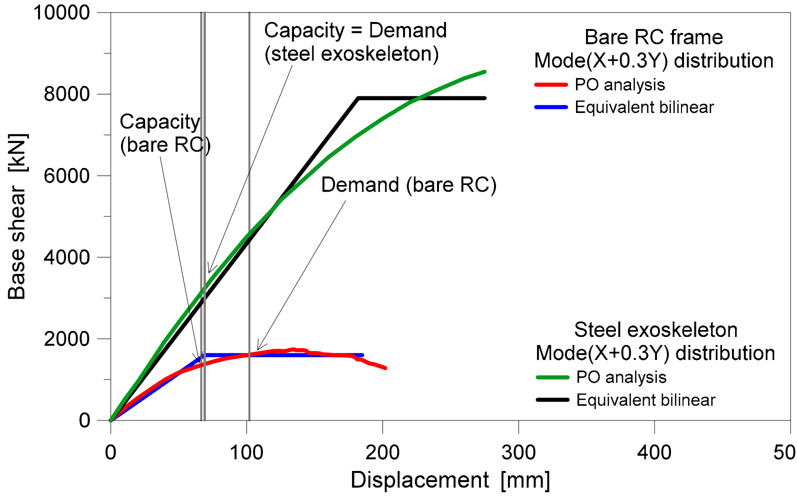


Figure 8. PO analysis results: comparison of bare RC building and existing building retrofitted by steel exoskeleton.

Table 3. Results of PO analysis in the post-intervention stage (steel exoskeleton).

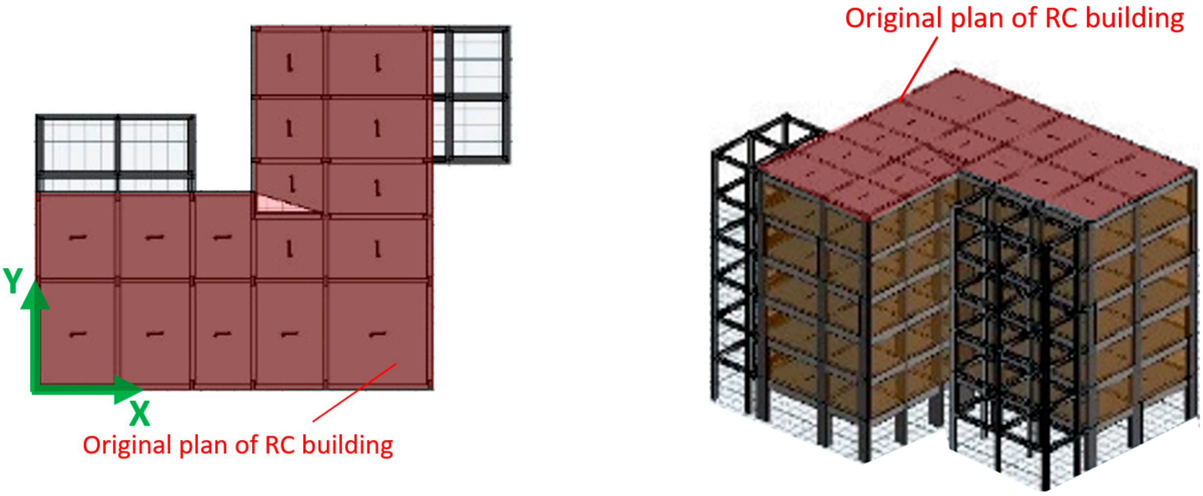
Push-Over	F_{max} (kN)	Γ	F^*_{max} (kN)	α_u/α_1	$S_e(T^*)$ (g)	q_*	*C* (cm)	*D* (cm)	*S*
Mode $+X+0.3Y$	4073	1.21	3371	1.87	0.456	1.2	6.91	6.91	1.00
Mode $+X-0.3Y$	6691	1.21	5538	1.76	0.583	1.0	6.91	5.56	1.24
Mode $-X+0.3Y$	6694	1.21	5540	1.69	0.584	1.0	6.91	5.56	1.24
Mode $-X-0.3Y$	4074	1.21	3372	1.71	0.456	1.2	6.91	6.91	1.00
Mode $+Y+0.3X$	4622	1.02	4527	2.01	0.384	1.2	8.18	8.18	1.00
Mode $+Y-0.3X$	9469	1.02	9275	1.70	0.549	1.0	8.18	5.90	1.38
Mode $-Y+0.3X$	9452	1.02	9259	1.68	0.544	1.0	8.18	5.96	1.37
Mode $-Y-0.3X$	4614	1.02	4520	1.75	0.38	1.2	8.18	8.18	1.00
Mass $+X+0.3Y$	7632	1.21	6317	1.66	0.644	1.0	6.28	5.03	1.24
Mass $+X-0.3Y$	9905	1.21	8198	1.82	0.703	1.0	6.23	4.61	1.35
Mass $-X+0.3Y$	9870	1.21	8169	1.16	0.703	1.0	6.91	4.61	1.49
Mass $-X-0.3Y$	8227	1.21	6810	1.23	0.643	1.0	6.61	5.04	1.31
Mass $+Y+0.3X$	9950	1.02	9746	1.77	0.561	1.0	7.33	5.78	1.26
Mass $+Y-0.3X$	13771	1.02	13489	1.97	0.66	1.0	6.54	4.92	1.33
Mass $-Y+0.3X$	13766	1.02	13484	1.36	0.654	1.0	8.18	4.96	1.64
Mass $-Y-0.3X$	9916	1.02	9713	1.46	0.556	1.0	8.18	5.84	1.40

Table 3 shows the PO analysis results of sixteen load combinations provided by numerical simulation, considering the accidental eccentricity between the mass centroid and the stiffness one.

As it is possible to observe, the C/D safety index is always greater than the unity value, and no critical situation is found, thus confirming the effectiveness of the proposed project intervention. In particular, the seismic safety index value was estimated at an average of ≈0.56 for the bare RC building and as ≈1 after the introduction of the steel exoskeleton. In conclusion, the analyses showed that the intervention on the case study RC building based on the steel exoskeleton could achieve appropriate safety indices for seismic purposes.

2.4. Application of RC Exoskeleton

Successively, the RC exoskeleton, as shown in Figure 9, was taken into account for the proposed structural reinforcement strategy and applied to the case study RC frame.



(**a**) (**b**)

Figure 9. Retrofit intervention for the bare RC building with RC exoskeleton: (**a**) plan and (**b**) axonometric views.

In this case, the exoskeleton is assumed to consist of an RC frame with beams and columns characterized by a rectangular cross-section of 0.60 × 0.60 m that are connected to the bare RC frame by a set of rigid links.

The efficiency and validity of such a retrofit intervention can be addressed by PO analyses. In this case, the RC retrofit qualitatively produces the same effects of the steel exoskeleton, but with less marked advantages (see Figure 10).

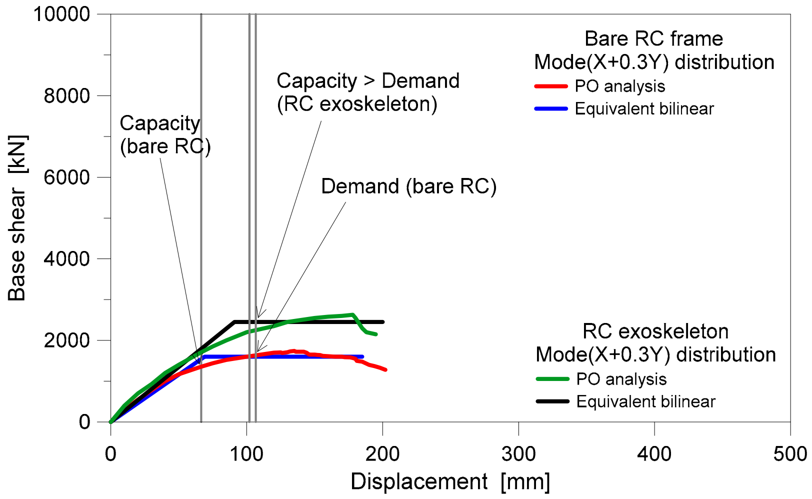


Figure 10. PO analysis results: comparison of bare RC building and existing building retrofitted by RC exoskeleton.

In fact, it is easy to verify that the increase in the overall lateral stiffness for the composite "bare frame + RC exoskeleton" system is lower than in the case of the steel exoskeleton, and this should possibly be considered with additional seismic devices [35]. Most importantly, it is possible to observe that the corresponding *C*/*D* safety indexes in Table 4 are greater than the unit, and no critical situations are found in terms of seismic performance, confirming the effectiveness and adequacy of the intervention.

Table 4 shows the results of the examined (sixteen) load combinations, provided by PO analyses, for the bare RC bare frame retrofitted with the RC exoskeleton.

Table 4. Results of PO analysis for the post-intervention stage (RC exoskeleton).

Push-Over	F_{max}	Γ	F^*_{max}	α_u/α_1	$S_e(T^*)$	q_*	C	D	S
	(kN)		(kN)		(g)		(cm)	(cm)	
Mode $+ X + 0.3Y$	3687	1.41	2606	1.70	0.317	1.1	10.67	10.21	1.04
Mode $+ X - 0.3Y$	5736	1.44	4055	1.43	0.373	1.0	9.69	8.70	1.11
Mode $- X + 0.3Y$	4494	1.41	3177	1.34	0.352	1.0	11.11	9.20	1.20
Mode $- X - 0.3Y$	3697	1.41	2614	1.23	0.327	1.1	11.08	9.92	1.11
Mode $+ Y + 0.3X$	5980	1.32	4527	1.18	0.368	1.0	12.41	8.80	1.41
Mode $+ Y - 0.3X$	9588	1.32	7260	1.23	0.461	1.0	13.03	7.03	1.85
Mode $- Y + 0.3X$	6101	1.32	4619	1.33	0.361	1.0	13.41	8.99	1.49
Mode $- Y - 0.3X$	4359	1.32	3301	1.32	0.310	1.0	12.55	10.46	1.20
Mass $+ X + 0.3Y$	6859	1.41	4849	1.93	0.402	1.0	8.76	8.05	1.08
Mass $+ X - 0.3Y$	6738	1.41	4764	1.00	0.412	1.0	10.38	7.87	1.31
Mass $- X + 0.3Y$	6614	1.41	4676	1.67	0.418	1.0	11.32	7.75	1.46
Mass $- X - 0.3Y$	6359	1.41	4496	0.87	0.409	1.0	11.13	7.92	1.40
Mass $+ Y + 0.3X$	7918	1.32	5995	1.94	0.427	1.0	12.65	7.58	1.66
Mass $+ Y - 0.3X$	7893	1.32	5976	1.63	0.451	1.0	13.40	7.19	1.86
Mass $- Y + 0.3X$	8167	1.32	6184	1.70	0.413	1.0	14.34	7.78	1.84
Mass $- Y - 0.3X$	7387	1.32	5593	1.10	0.396	1.0	10.41	8.17	1.27

2.5. Summary and Discussion of Results

Overall, both the steel and RC exoskeleton solutions adopted in the present study proved to offer effective contributions to the bare RC building from a seismic point of view (Figure 11).

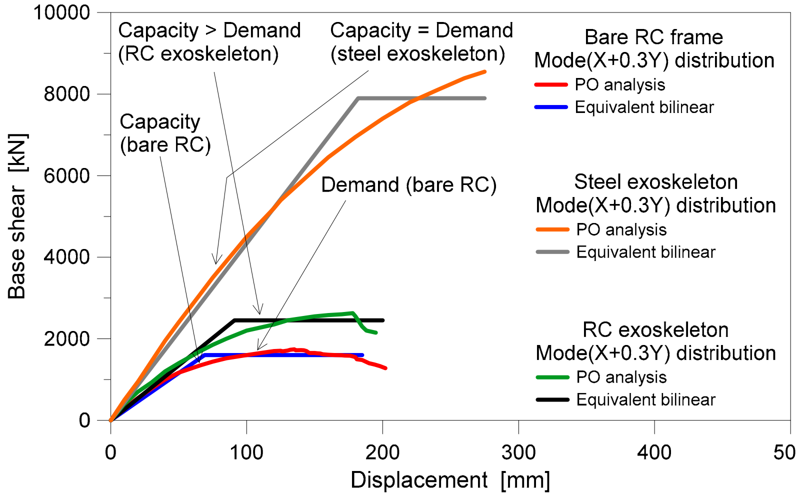


Figure 11. PO analysis results: comparison of bare RC building and existing building retrofitted with steel or RC exoskeletons.

The retrofit intervention based on the use of a steel exoskeleton is certainly more interesting, both from the point of view of mechanical effectiveness (strength and ductility) and from the point of view of in-field construction. Moreover, the steel exoskeleton adds high stiffness to the composite system, compared to the RC one [35,36]. From a quantitative point of view, the different behaviour of examined solutions can thus be clearly distinguished in Figure 11. In this regard, it is worth noting—for both cases—that the fixing joints between the exoskeleton and the existing building have been considered as rigid, while their role could be maximized in efficiency by means of dissipative elements.

3. Conclusions

The retrofit of existing buildings, both in terms of structural and energy efficiency, is nowadays a crucial issue. As such, a holistic, multi-disciplinary approach should be taken into account. In the context of an extended research project, this paper presented the first steps of such an approach. In particular, a set of PO analyses for a six-story RC building was presented to define the performance point of the composite system given by "bare RC frame + exoskeleton". The numerical results showed that steel exoskeletons, compared to RC, can be more efficient in terms of strength and ductility capacity, despite a relatively high stiffness. In any case, exoskeletons allow buildings to preserve their activities during the intervention. The results of experimental tests on basic materials, as well as the energy potential of the composite system, will be presented in future work.

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