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Chapter

Energy and Seismic Rehabilitation of RC Buildings through an Integrated Approach: An Application Case Study

Antonio D'Angola, Vincenzo Manfredi, Angelo Masi and Marianna Mecca

Abstract

The high number of existing buildings in Italy without adequate seismic and thermal performances requires the definition of integrated retrofitting techniques in order to improve the seismic performance and to reduce energy losses at the same time. On one hand, an integrated approach appears mandatory considering that improving only the energy efficiency of nonseismic buildings leads to an increase of their exposure and, therefore, of their risk in the case of seismic events. On the other hand, seismic strengthening without an adequate thermal assessment and rehabilitation could compromise living comfort and energy maintenance costs. In this context, an application of integrated approach for the rehabilitation of reinforced concrete (RC) existing buildings has been proposed referring to a case study representative of the Italian building stock. Different configurations of infill panels have been considered in order to analyze both energy and seismic performance. Monthly quasi-steady state and hourly dynamic models have been used for the calculation of the energy need of buildings located in different Italian climate and seismic zones. Seismic performances have been evaluated by means of incremental nonlinear dynamic analysis (IDA). As-built and post-retrofit performances have been compared in order to evaluate the effectiveness of the proposed intervention solutions.

Keywords: existing RC buildings, integrated approach, thermal insulation, energy efficiency, seismic strengthening, infill walls

1. Introduction

In Europe, about 25 billion m^2 of available floor space (data relevant to 27 EU member states in 2011 plus Switzerland and Norway) was built up in the past. A predominant part of this surface, about 75%, is made up of residential buildings (64% single family houses, 36% apartment blocks), while the other part (25%) consists of more complex and heterogeneous nonresidential buildings. More than 40% of residential buildings were constructed before the 1960s, with the largest percentages of older buildings in the United Kingdom, Denmark, Sweden, France, Czech Republic, and Bulgaria [1]. As a result, beyond the well-known deficit of seismic protection, dramatically pointed out by past earthquakes, also the energy performances of the European buildings are expected to be generally poor. In fact, energy consumed in buildings is one of the main CO_2 emission sources in Europe.

As for Italy, most of the residential buildings (77%) were constructed before 1981, when only 25% of the national territory was classified as seismic. These buildings were not designed considering seismic actions; therefore, they are generally characterized by high vulnerability, as clearly shown by recent earthquakes (e.g., L'Aquila 2009, Emilia 2012, central Italy 2016) [2–5].

In addition to seismic deficit, the Italian building stock is also characterized by a large deficit of thermal insulation. In fact, the first regulation, addressing thermal performance criteria, was introduced in 1991 [6], when about 88% of the present Italian building stock had already been realized.

Due to the huge number of buildings having inadequate seismic and energy performances, both in Europe and in Italy, an integrated approach in the design of interventions able to provide multiple beneficial effects is strongly required in view of deploying an effective rehabilitation program. On the contrary, uncoupled rehabilitation solutions appear ineffective. In fact, in earthquake-prone areas, thermal rehabilitation interventions designed neglecting seismic actions could determine an increase of the exposure in terms of building value without adequate seismic protection. Similarly, seismic retrofitting interventions paying little or no attention to thermal rehabilitation could compromise comfort and energy maintenance costs since they can induce higher heat loss (e.g., by simply adding RC shear walls). As an example, interventions that either do not eradicate or—even worse—introduce thermal bridges, due to discontinuities or gaps in the insulation material, can compromise thermal insulation.

In the framework of an integrated approach, the chapter focuses on the impact on the seismic performance of some rehabilitation techniques generally adopted to enhance the thermal performance of infill walls. To this purpose, incremental dynamic analyses (IDAs, [7]) have been carried out on a prototype RC building—representative of the existing building stock—before and after thermal rehabilitation. Specifically, an intervention carried out by replacing the existing masonry infill walls with new elements able to ensure an adequate thermal insulation is considered. Furthermore, the improvement in both seismic and thermal performances through the so-called "double skin" [8, 9] intervention technique, that is, by adding new infilled frames adequately linked to the existing ones, is analyzed.

Energy performances have been investigated following the European standard methods by means of a quasi-steady state approach, based on monthly averaged climate data, and of a dynamic approach, based on hourly climate data. Both energy and seismic analyses have been performed considering two different Italian cities, namely Palermo (Southern Italy) and Milan (Northern Italy), characterized by different climatic conditions and seismic hazard.

2. Case study: building type description and modeling

A six-storey RC framed structure representative of the nonseismic post-1971 Italian building stock has been considered as case study. It has a rectangular shape in plan (**Figure 1**) with total dimensions 21.4 × 11.8 m^2 (X and Y direction, respectively) and constant interstorey height equal to 3.05 m. As a consequence of the design carried out only for vertical load and the orientation of the one-way RC slab spanning along the longitudinal X direction, frames are arranged in the transversal Y direction only. Rigid beams (0.30 × 0.50 m^2) are arranged along the exterior frames,

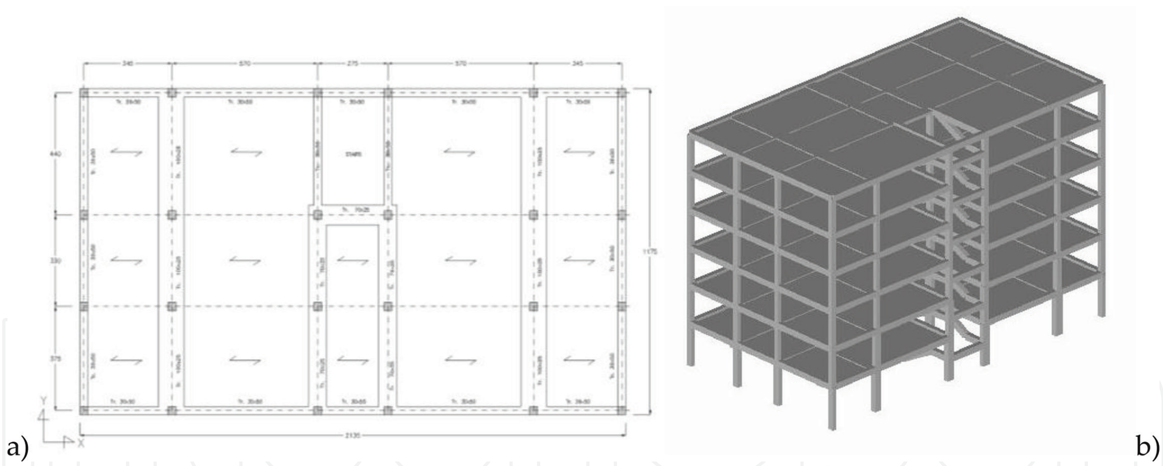

Figure 1.
In plan layout of the building type under study (a) and three-dimensional (3D) view of the model (b).

while internal beams are flexible (0.70 × 0.25 and 1.00 × 0.25 m^2). Specifically, along the longitudinal direction X, rigid beams are present only in the exterior frames. Columns have generally cross-sectional dimensions equal to 0.30 × 0.30 m^2, except for some columns of the lower storeys whose dimensions range from 0.30 × 0.40 to 0.30 × 0.55 m^2. The staircase substructure is placed in a symmetric position with respect to the Y direction and has knee-type beam with dimension 0.30 × 0.50 m^2.

According to the considered construction period, infill panel is a multilayer type constituted by two hollow brick walls (8 cm + 12 cm, respectively, internal and external layer) with an air gap (10 cm) and internal/external cement plaster/finish coats (2 cm + 2 cm). Windows are made by wood and a single glass and are characterized by high values of transmittance.

Reinforcement details have been obtained by means of a simulated design procedure [10] with reference to the codes in force and the constructive practice of the period.

Both energy and seismic analyses have been carried out by considering three different configurations:

1. C1: as-built;
2. C2: external existing layer of the as-built infill (12 cm thick) replaced by new one (20 cm thick) with high thermal insulation properties;
3. C3: new 20-cm-thick infill panels placed on new RC frames added to the as-built configuration (C1) and effectively connected to the existing frames.

2.1 Energy retrofitting modeling

The energy balance has been performed in the framework of the monthly quasi-steady state and of the hourly dynamic approaches, focusing on the second floor of the building, with S_u = 219.68 m^2 of useful floor area, V = 751.96 m^3 of volume, and surface-to-volume ratio S/V = 0.6, being S the total external surface.

The boundaries for the calculation of the heating and cooling energy values consist of all the elements separating the conditioned single-zone space from the external environment or unconditioned spaces: external walls and windows. Floors and ceiling are excluded from the envelope representing boundaries with conditioned zones.

The mathematical models adopted to investigate the energy demand of the building are as follows:

1. the simplified monthly quasi-steady state method based on the European Standard ISO 13790 and the UNI 11300:2014, calculating the seasonal energy balance of the building (time interval depending on the climate zone) [11];

2. the hourly dynamic approach based on the recent European Standard ISO 52016 in which a more complex (with respect to the ISO 13790:2008) and an extensive lumped model adopting a resistance-capacitance (RC) network to perform the hourly calculation is considered [12, 13].

The quasi-steady state model includes all sources and sinks of energy, as well as all energy flows through its envelope. The dynamic effects are taken into account by introducing dimensionless utilization factors for heating and cooling [12] that depend on the building inertia by means of the building time constant.

The envelope encloses the volume with a fixed designed temperature for all weather conditions by the use of heating or cooling source energy. Heat flows depend on external and internal influence factors and can be classified as follows:

- transmission losses, Q_{tr}, which flow through the building envelope from inside to outside by conduction or heat transfer;

- ventilation losses, Q_v, caused by exchange of warm indoor air with colder outdoor air through joints by infiltration or exfiltration, respectively. In addition, room air can be exchanged through open windows or by a mechanical ventilation system. Ventilation is indispensable to assure the hygienically necessary air exchange rate;

- solar gains, Q_{sol}, due to the irradiation of solar energy through windows and other transparent or translucent constructional elements. Also added to the solar gains, it is that part of the solar heating of the opaque building envelope, from which the indoor area benefits. Solar heat sources result from the solar radiation normally available in the locality concerned, the orientation of the collecting areas, the permanent shading, the solar transmittance and absorption, and thermal heat transfer characteristics of collecting areas;

- internal gains, Q_{int}, represented by the heat released by persons, appliances, computers and other electric devices, as well as from illumination (metabolic heat from occupants and dissipated heat from appliances, dissipated heat from lighting devices, heat dissipated from or absorbed by hot and mains water and sewage systems, heat dissipated from or absorbed by heating, cooling and ventilation systems, heat from or to processes and goods).

The amount of energy, which is necessary to maintain the desired room temperature by compensating the excess of losses (Q_{tr} and Q_v) compared to the gains (Q_{int} and Q_{sol}), is represented by the energy need for heating, Q_H, normalized by the corresponding useful area. To achieve a remarkable reduction in energy need, especially in colder climate zone, renewable energy technologies should be implemented and integrated in the building [14, 15].

Finally, the hourly dynamic model is based on the ISO 52016 [12, 13] in which building elements are modeled by means of lumped parameters. It is worth noting that adopting dynamic models in performing energy analysis, both in design of new buildings and in rehabilitation of existing buildings, can reduce the energy demands for HVAC systems.

2.1.1 The effects of thermal bridges

By following the definition given in the European Standard EN ISO 10211:2017, thermal bridges are part of the building envelope where the otherwise uniform thermal resistance is significantly changed by full or partial penetration of the building envelope by materials with a different thermal conductivity, or a change in thickness of the fabric, or a difference between internal and external areas, such as occurring at wall, floor, and ceiling junctions. They can contribute to increase the energy demand during heating and cooling seasons and can create interior surface condensation problems. Thermal bridges can be classified as follows [11]: (i) repeating thermal bridges, occurring with a regular pattern; (ii) nonrepeating thermal bridges, such as the bridging of a cavity wall by a single lintel; (iii) geometrical thermal bridges, placed at the junction of two planes. Some examples of thermal bridges in building envelopes are corners that provide additional heat flow paths, window sills, floor to wall junctions, balcony supports, lintels, gaps in insulation, and debris in wall cavity.

Thermal bridges produce an additional heat loss affecting the energy balance. It is accounted for by means of the linear thermal transmittance, ψ, that is, the rate of heat flow per temperature degree difference per unit length of the junction. In order to reduce heat transmission losses, numerical investigations have been carried out introducing a thermal barrier with different size. In the present chapter, a polystyrene coat of variable size has been added and the effects of thermal insulation have been numerically investigated by using a 2D finite element numerical model.

2.2 Seismic modeling

Structural modeling was defined according to a nonlinear macromodeling approach in the OpenSees [16] framework. At both ends of each structural member, a bending moment-rotation (M-δ) relationship was defined by adopting the Ibarra, Medina, and Krawinkler model [17] (**Figure 2**), whose backbone parameters were evaluated according to Haselton and Deierlein [18].

For members having brittle failure, the M-δ relationship was appropriately modified according to the Sezen model [19] in order to account for a lower

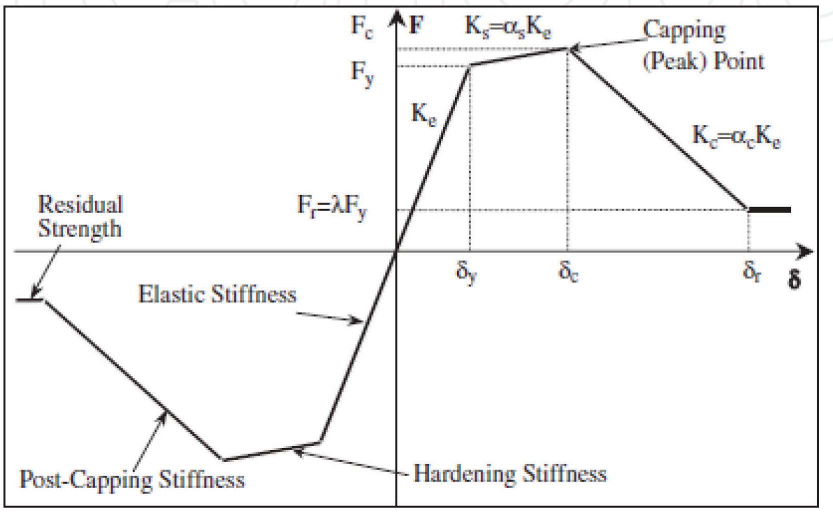

Figure 2.
Adopted backbone curve for structural members (from Ibarra et al. [17]).

deformation capacity experienced in case of failure in shear. On the basis of the mechanical properties of the constituent materials typically found in real buildings of the period under consideration [20], mean concrete strength value (f_{cm}) equal to 20 MPa, and mean steel strength value (f_{ym}) equal to 400 MPa were assumed in evaluating the structural capacity.

In the different configurations considered in the study, infill panels were modeled by using a nonlinear equivalent diagonal strut according to the Bertoldi model [21].

Consistent with experimental results (e.g., [22]), for the infill type considered in the as-built configuration, the compressive strength and the elastic modulus are equal to 1.1 and 1800 MPa, respectively. As for infills in both C2 and C3 configuration, the adopted values are 4.0 and 3300 MPa, respectively, for the compressive strength and the elastic modulus, as suggested in [23].

3. Thermal and seismic rehabilitation design

The integrated intervention here investigated for the rehabilitation of the RC existing buildings under study consists of the following:

- replacing the external existing infill panel of the as-built configuration (C1) with new one having better thermal insulation properties (C2 configuration);

- adding new infill panels to the as-built configuration (C1) placed on new RC frames effectively connected to the existing ones (C3 configuration).

According to the European Standard EN ISO 6946, 10077, and 12631, the total thermal transmittances for cases C1, C2, and C3 are 0.69, 0.28, and 0.28 W m^{-2} K^{-1}, respectively. In dynamic conditions, heat transfer coefficients, including the thermal bridge contribution, have been calculated according to the ISO 13789:2017.

In the following, starting from the assessment results obtained for the as-built configuration (C1), both energy and seismic performances of the two proposed integrated solutions have been evaluated with respect to two different locations, namely Milano and Palermo.

3.1 Energy analysis

Numerical simulations have been performed in order to calculate the energy need in configurations C1, C2, and C3. Results have been obtained in both quasi-static and dynamic condition. Two different locations have been considered: (i) Milan, located in the Italian climate zone E (heating degree days in the range 2101–3000, heating period from the 15th of October to the 15th of April and collects about 4000 cities), and (ii) Palermo, located in the Italian climate zone B (heating degree days in the range 601–900, heating period from the 1st of December to the 31st of March and collects about 150 cities).

3.1.1 Thermal bridges and minimization of heat transmission losses

Preliminary numerical investigations, in the framework of the monthly quasi-steady state model, have been carried out to evaluate the contribution of thermal bridges to the energy balance of the building. Five different cases, labeled (a)–(e) have been considered:

a. as-built (C1 configuration) without thermal bridges;

b. as built (C1 configuration) with thermal bridges;

c. C2 configuration without thermal bridge contribution;

d. C2 configuration with thermal bridge contribution;

e. C2 configuration with thermal bridge contribution and additional thermal barrier with different width, s.

The thermal bridges considered in the simulations are pillars, external corners, and roof-to-wall interfaces, as shown in **Figure 3**.

Thermal bridge contributions can be calculated by modeling the corresponding building component connections as input data for a 2D heat flow numerical code. As an example, in **Figure 4**, the temperature fields across the thermal bridge, obtained by means of the 2D heat flow code, are reported. Specifically, simulation refers to the cases (d) and (e), showing the effectiveness of the thermal barrier to minimize heat transmission losses.

Results obtained by numerical simulations are presented in **Table 1**, where heat transmission losses are reported for the cases (a)–(e).

The first conclusion is the importance of accounting for the thermal bridges for an accurate evaluation of heat thermal losses. Comparing results obtained from cases (c) and (d), one can conclude that the contribution of thermal bridges to the calculation of heat transmission losses is close to 40%, thus such contribution cannot be neglected. Therefore, a parametric study to define an effective solution to minimize thermal bridge losses has been carried out. To this end, a thermal barrier made up of a continuous external polystyrene coat has been added, by varying its thickness. **Figure 5** shows that a 4.0 cm coat appears an effective solution, being able to reduce thermal bridge losses up to 35%.

Finally, the influence of thermal bridges is evaluated also by using the dynamic model. As an example, **Figure 6** shows the total heat transmission losses and the time evolution of the temperature of the internal air obtained in Palermo for the configuration C2.

Results show that, in dynamic conditions, the contribution of thermal bridges can influence dramatically the evaluation of transmission losses that can be underestimated up to a factor 2.

3.1.2 Energy performances: monthly quasi-steady state and hourly dynamic models

Numerical simulations have been performed both in quasi-static and dynamic conditions for the two different locations under study, that is, Milano and

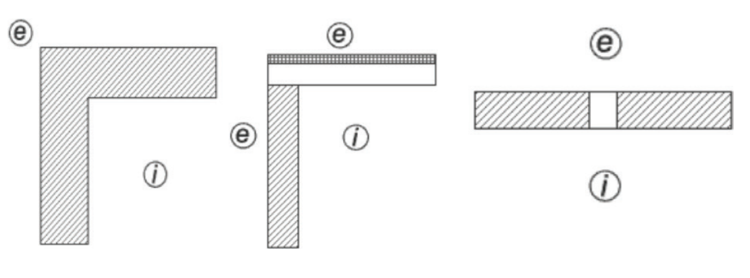

Figure 3.
Thermal bridges: corners (left side), roofs and ceiling (center), and pillars (right side).

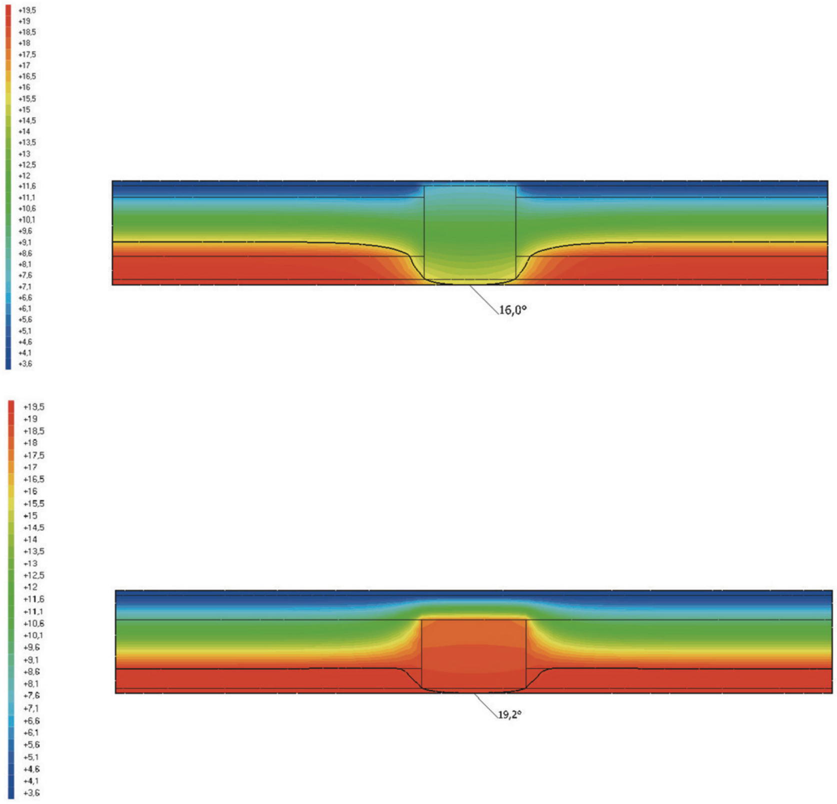

Figure 4.
Thermal bridge simulation of pillars with (on the bottom) and without (on the top) additional 40 mm of thermal barrier.

	Case a	Case b	Case c	Case d	Case e (s = 40mm)
Q_{tr}	91.76	116.21	69.78	104.05	75.44
Q_{tr} pillars				91.83	75.13
Q_{tr} pillars and corners				93.33	75.44

Table 1.
*Total heat transmission losses (in [*kWh m^{-2} K^{-1}*]).*

Palermo. In **Figure 7**, the results computed with the monthly quasi-steady state and hourly dynamic models are compared, both in cooling and in heating conditions. In the simulations, the building volume is divided considering two thermal zones, that is, night and day rooms, with different set point temperatures (19 and 21°C), and the HVAC system is considered active only for 10 hours/day in the case of dynamic simulation. Results show that dynamic and static methods could produce different results due to the capability of the dynamic model of reproducing more realistically the behavior of the building (HVAC system, internal gains or losses,…).

Finally, in **Table 2**, the total thermal energy for heating, Q_H, and cooling, Q_C, are reported, both for Milano and Palermo by using the hourly dynamic and the monthly quasi-steady state models. Results show the effectiveness of C2 and C3 energy retrofits. In particular, C3 configuration is the best solution both in Palermo and Milano from the point of view of the energy saving. However, it should be highlighted that this is a partial result, as the analysis of the seismic performance, together with the cost of the total retrofit intervention, must be considered in a complete analysis.

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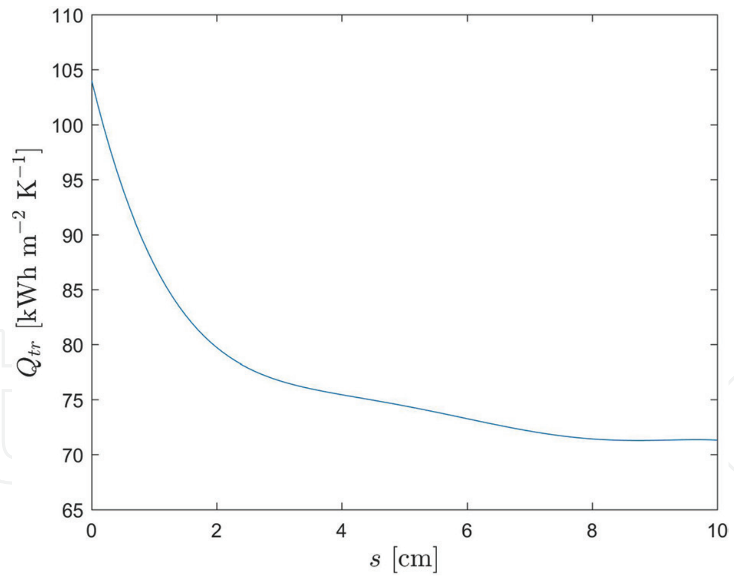

Figure 5.
Total heat transmission losses obtained for the C2 configuration including the effects of thermal bridges and considering an additional thermal barrier.

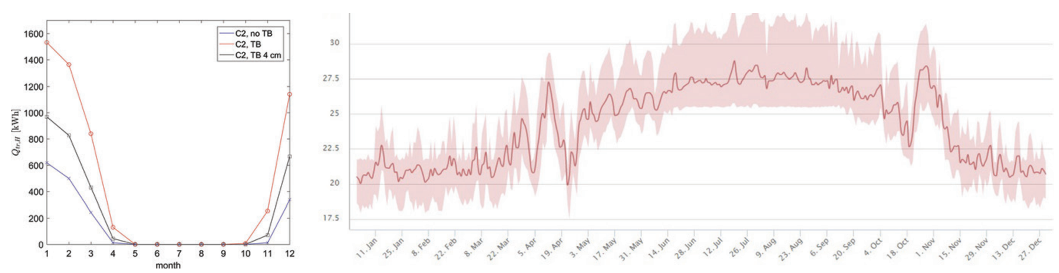

Figure 6.
Total heat transmission losses obtained for the C2 configuration. In the simulations, thermal bridges (TB) and an additional thermal barrier of 4 cm are considered. Simulations are obtained by means of the dynamic model and refer to the building located in Palermo.

3.2 Seismic analyses

Seismic performances have been evaluated through the incremental dynamic analysis (IDA) [7]. In order to account for the effects on the structural response due to record-to-record variability, 10 accelerograms selected in the RINTC project [24] and scaled up to the collapse have been considered. The main seismic parameters of the considered accelerograms are reported in [9] and briefly summarized in **Table 3**.

Results are reported in **Figure 8**. Specifically, the IDA median curves, evaluated for the considered configurations in terms of spectral pseudoacceleration value corresponding to the scaling factor of the record and the maximum base shear value, are displayed separately for X (**Figure 8a**) and Y (**Figure 8b**) in-plane direction. The spectral-pseudoacceleration $Se(T_0)$ has been evaluated at the fundamental period of each considered configuration. In the same figure, the points relevant to both damage limitation (DLLS) and life safety (LSLS) limit state, calculated in accordance with the Italian code [25], are also displayed.

With reference to C1 configuration (i.e., "as-built"), the seismic intensities evaluated in the X direction at DLLS and LSLS are equal to 0.105 and 0.163 g, respectively. In the Y direction, mainly due to the role of the staircase substructure (which determines a greater stiffness with respect to the X direction and a brittle behavior of the relevant short columns), DLLS is achieved at 0.138 g, which is about

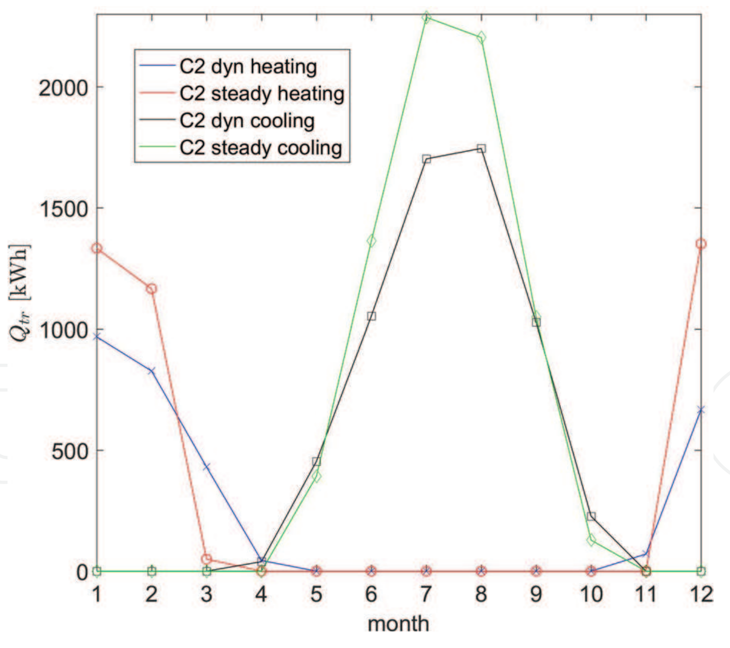

Figure 7.
Total transmission losses (heating and cooling) obtained for the C2 configuration. Simulations are obtained by means of the monthly quasi-steady state and hourly dynamic models and refer to the building located in Palermo.

Case		Milano			Palermo		
		C1	C2	C3	C1	C2	C3
Dynamic (kWh)	Q_H	28,773.69	21,078.01	9013.55	12,627.31	8533.53	8748.46
	Q_C	5218.24	6345.19	6916.87	7101.93	7795.36	8075.09
Quasi-steady state (kWh)	Q_H	18,665.85	14,922.19	15,205.30	5443.9	4129.12	4098.47
	Q_C	3695.57	4025.78	3809.08	7142.80	7275.69	7401.05

Table 2.
Total thermal energy for heating and cooling in Milano and Palermo.

30% higher than that evaluated in the X direction (0.105 g), whereas a remarkably lower value (0.110 g) than that evaluated in the X direction (0.163 g) is found for LSLS.

In order to estimate the seismic deficit, the above reported intensity values (capacity, $S_{e,C}$) have been compared with the seismic hazard (demand, $S_{e,D}$) evaluated for Milan and Palermo (representative of sites with low and medium seismic hazard) according to the Italian hazard map [26] (soil A). The ratio between the capacity and the demand value ($\alpha = S_{e,C}/S_{e,D}$) for both limit states has been computed, and the results are reported in **Table 4**.

Except for the site of Palermo at LS limit state, both αDL and αLS are always higher than 1 (i.e., no seismic intervention is required). αLS evaluated for Palermo is equal to 0.81, thus asking for a strengthening intervention to guarantee adequate structural safety.

As a consequence of the greater mechanical properties of the infill panels adopted for C2 configuration, a greater base shear value is found with respect to C1 configuration, as shown in **Figure 8**. In terms of seismic intensity values relevant to both DLLS and LSLS, they are equal to 0.130 and 0.197 g in the X direction (to be compared with 0.105 and 0.163 g in the C1 configuration, respectively), while, in

ID	PGA (g)	PGV (cm/s)	$S_{e,max}$ (g)	HI (m)
1	0.046	1.61	0.167	0.049
2	0.035	2.13	0.125	0.054
3	0.043	0.41	0.183	0.054
4	0.021	0.83	0.086	0.052
5	0.070	0.26	0.339	0.047
6	0.050	2.37	0.089	0.052
7	0.029	0.45	0.108	0.061
8	0.009	0.85	0.037	0.083
9	0.026	0.31	0.105	0.064
10	0.028	0.56	0.147	0.055

Table 3.
Seismic parameters of the considered accelerograms in terms of peak ground acceleration (PGA), peak ground velocity (PGV), maximum spectral pseudoacceleration ($S_{e,max}$), and Housner intensity (HI).

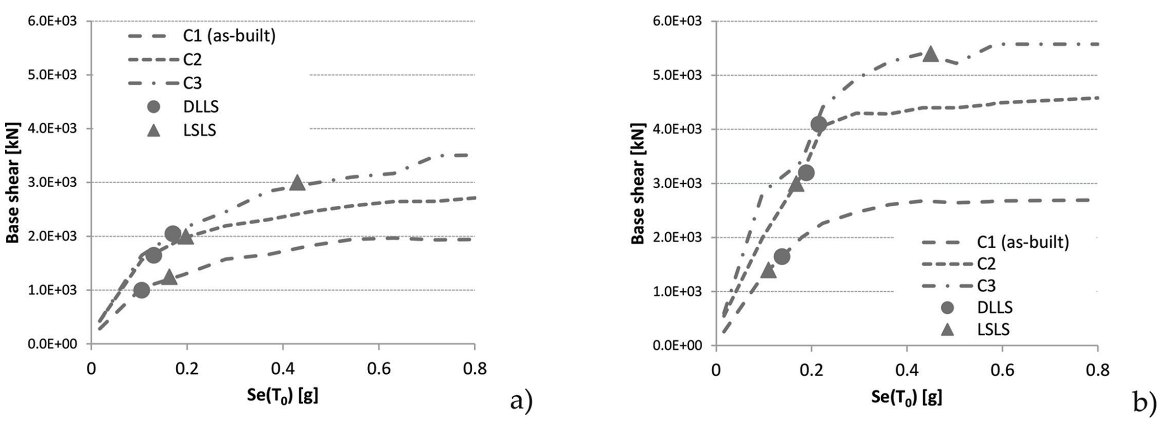

Figure 8.
Spectral pseudo-acceleration versus maximum base shear curves relevant to the three considered configurations, obtained for X (a) and Y (b) direction by considering median values from IDA analyses.

	DLLS			LSLS		
Site	**Se,C (g)**	**Se,D (g)**	**αDL = Se,C/Se,D**	**Se,C (g)**	**Se,D (g)**	**αLS = Se,C/Se,D**
Milan	0.105	0.015	7.0	0.110	0.042	2.6
Palermo		0.039	2.7		0.135	0.81

Table 4.
α ratio values between seismic capacity Se,C and demand Se,D evaluated for both DL and LS limit state.

the Y direction, they are 0.189 and 0.168 g (0.138 and 0.110 g in the C1 configuration, respectively). Consequently, the minimum αLS value evaluated for the site of Palermo goes from 0.81 to 0.93 (**Table 5**).

As for C3 configuration (i.e., new infilled RC frames added to the as-built configuration C1 and effectively connected to the existing frames, **Figure 9**), **Figure 8** summarizes the results obtained from the IDA analyses and the comparison with the other configurations (C1 and C2). In terms of seismic capacity evaluated at the two considered limit states, the values at LSLS are equal to 0.430 and 0.450 g for X and

	C1 ("as-built")			C2			C3		
Site	**Se,C (g)**	**Se,D (g)**	**α = Se,C/ Se,D**	**Se,C (g)**	**Se,D (g)**	**α = Se,C/ Se,C**	**Se,C (g)**	**Se,D (g)**	**α = Se,C/ Se,C**
Milan	0.110	0.042	2.60	0.168	0.057	2.95	0.430	0.063	6.82
Palermo		0.135	0.81		0.180	0.93		0.200	2.15

Table 5.
Comparison between seismic capacity values and hazard demand relevant to as-built and postintervention configurations evaluated for LS limit state.

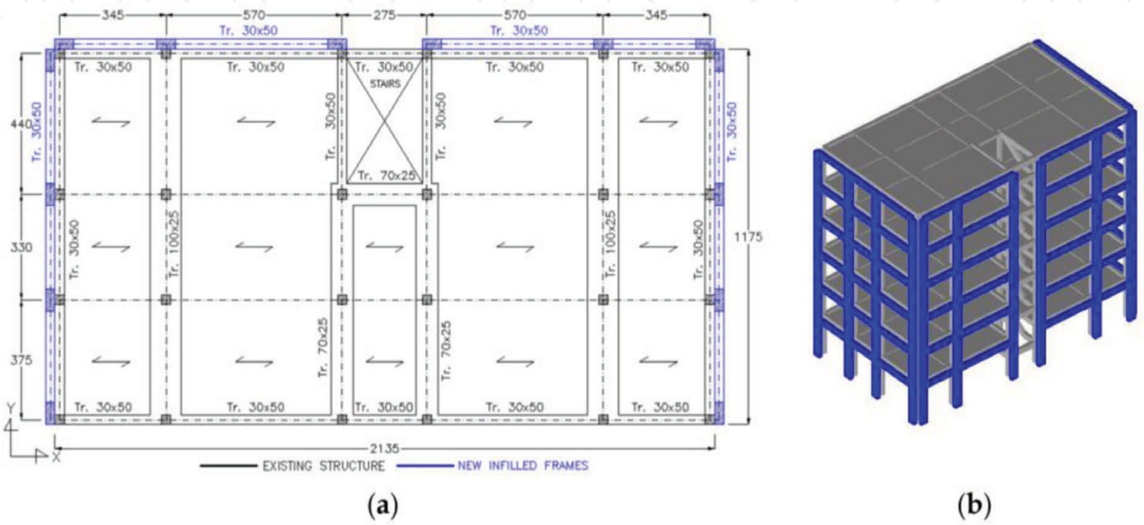

Figure 9.
C3 configuration: in plan layout of the retrofitted building (a) and 3D view of the model (b).

Y directions, respectively, while for DLLS, intensity values are 0.170 and 0.215 g for X and Y directions, respectively. Consequently, a full seismic rehabilitation (i.e., αLS ratio greater than 1) has been achieved also for Palermo, as reported in **Table 5**.

4. Conclusions

In the present work, an application of integrated rehabilitation intervention on reinforced concrete (RC) existing buildings has been presented. A case study located in two different cities, Milano and Palermo, having different climatic conditions and seismic hazard values, has been investigated.

The building under study has been analyzed considering three different configurations, with different arrangement and features of the infill panels, in order to highlight their role on both thermal and seismic performances. Quasi-static and dynamic methodologies have been used for the calculation of the energy demand, highlighting the importance of accounting for thermal bridges in the investigations. As for seismic performance, the results of the incremental nonlinear dynamic analyses show that infill panels having greater thermal and mechanical properties increase the seismic capacity. Nevertheless, a full seismic rehabilitation for the site with the highest seismic hazard (i.e., Palermo) has been achieved only by strengthening the RC structure with additional RC frames.

Future work, besides including additional case studies (building types, different seismic and climate sites,…), will be devoted to set up and propose a methodology for integrated rehabilitation interventions. Further, economic aspects will be better investigated with the aim of finding the cost-optimal integrated retrofit solution including the impact of the expected economic losses due to seismic damage throughout the building life cycle.

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