sustainability

IMPACT FACTOR 3.3

CITESCORE 6.8

Article

The Key Role of Floors for the Sustainability of Retrofit Interventions in Older Existing Reinforced Concrete Buildings

Marco Vona, Angelo Anelli, Francesco Paolo Del Giudice and Benedetto Manganelli

Special Issue
Urban Resilience and Sustainability—Assessment Tools

Edited by
Prof. Dr. Benedetto Manganelli and Prof. Dr. Pierluigi Morano

MDPI

https://doi.org/10.3390/su16145862

sustainability

MDPI

Article

The Key Role of Floors for the Sustainability of Retrofit Interventions in Older Existing Reinforced Concrete Buildings

Marco Vona [1,*], Angelo Anelli [2], Francesco Paolo Del Giudice [3] and Benedetto Manganelli [1]

[1] School of Engineering, University of Basilicata, Ateneo Lucano Avenue 10, 85100 Potenza, Italy; benedetto.manganelli@unibas.it
[2] Italian National Research Council—IGAG, 00010 Rome, Italy; angelo.anelli@igag.cnr.it
[3] Department of Architecture and Design, University of Rome "Sapienza", Borghese Sq. 9, 00186 Rome, Italy; francescopaolo.delgiudice@uniroma1.it
* Correspondence: marco.vona@unibas.it

Abstract: In recent decades, the seismic performance of existing reinforced concrete (RC) buildings has played a key role. Nevertheless, the performance and reliability verification of important structural elements such as floors has often been neglected. Floors are primary structural elements that can affect the life cycle life of a building. However, the widespread lack of maintenance planning over time and the original construction practice (which was not always correct) are frequently the cause of unpredictable local or global collapse. In addition, although recent standards and codes recognize the importance of floors by prioritizing their verification with respect to gravitational load conditions, the verification of floor reliability with respect to the load combinations required by modern standards and codes is often not satisfied. Consequently, the intervention costs could be significantly affected by the floor conditions, and their overall amount might even discourage the implementation of interventions. The main purpose of this study is to evaluate the effects (in terms of sustainability) of interventions on residential RC buildings, considering the need to retrofit their existing floors. To this aim, the most vulnerable and potentially most degraded floor types are identified, and their capacity–demand relationships are evaluated. In the case of unverified floors, the main and most popular intervention methods are evaluated and related to the overall intervention costs, taking into account the main uncertainties in performance and cost predictions. The problems and critical issues of floors are key in determining the safety of the building and the cost-effectiveness (i.e., sustainability) of the retrofit intervention. Professionals and decision makers could benefit from the proposed study cost model to define intervention strategies on a regional or national scale.

Keywords: seismic risk analysis; existing buildings; cost–benefit analysis; sustainability of retrofitting

Citation: Vona, M.; Anelli, A.; Del Giudice, F.P.; Manganelli, B. The Key Role of Floors for the Sustainability of Retrofit Interventions in Older Existing Reinforced Concrete Buildings. *Sustainability* **2024**, *16*, 5862. https://doi.org/10.3390/su16145862

Academic Editor: Antonio Caggiano

Received: 10 May 2024
Revised: 13 June 2024
Accepted: 1 July 2024
Published: 10 July 2024

1. Introduction

In recent years, the issue of retrofitting existing buildings has become fundamental in modern civil engineering. In countries with high seismic activity, seismic risk assessment is a critical issue and has been widely addressed, providing important scientific and regulatory references, as well as guidelines for professional practice. In addition, methods for prioritizing and interventions based on cost–benefit analysis have been proposed and applied both on a large spatial scale and for individual buildings [1–6].

Around the world [7] (e.g., in Europe [8], U.K. [9], the United States [10], China [11], India [12]), various codes and standards have been established to improve the sustainability of the building stock (often based on decarbonization). However, current cost models do not explicitly consider the possibility of having to intervene directly on the floors of existing buildings, especially on a national and regional scale [13]. In addition, the types of retrofit work on reinforced concrete buildings are performed from the outside, for obvious cost reasons. In these cases, any intervention on the floors makes seismic retrofitting uneconomical.

A cost–benefit analysis is fundamental to define intervention strategies. It represents a key element in risk mitigation strategies and in post-earthquake repair and adaptation phases [14]. In the latter cases, while much valuable information is available, post-earthquake data [15–19] cannot be used in the assessment of intervention costs for buildings in ordinary conditions. It should be noted that only a few intervention models have been defined for ordinary pathologies on the basis of an extensive cost–benefit analysis.

This weakness was probably decisive in the elimination of the so-called superbonus [20,21]. In fact, considering the sismabonus as a possibility to implement a large-scale mitigation strategy, its proper implementation had to be based on a priority of interventions that maximize its beneficial effects for the same costs.

The need for building-safety strategies must also take into account that the age of residential buildings is high in many countries. In particular, in Italy, numerous reinforced concrete (RC) buildings in residential use are now quite old [22]. A large proportion of these were built with materials, design and construction procedures, and regulations that cannot guarantee the safety of inhabitants after many years. Many of these buildings have now exceeded the working life defined by modern codes and regulations for the design of new buildings.

Paradoxically, various building retrofit strategies have been encouraged in recent years, both structural [14] and in terms of energy efficiency [23,24]. In these strategies, the lack of specific intervention measures regarding the verification of gravity loads, with particular reference to floors, must be emphasized even more.

In this regard, on the one hand, the regulations directly and clearly identify the obligation to ensure construction safety for all interventions in the same way as new buildings. The verification of gravity and live loads is carried out in terms of the ratio between the maximum value of the variable vertical overload supportable by the i^{th} structural element of the construction and the value of the variable vertical overload that would be used in the design of a new construction ($\zeta_{v,i}$, in [24]). On the other hand, the procedures in case of failure of verification do not seem to be sufficiently studied.

Both the European and Italian Code define safety levels for all types of actions and their combinations. However, it should be emphasized that while the gravity and live loads for existing structures are the same as for new structures, a reduction may be considered acceptable (perhaps for economic reasons) for seismic actions. Retrofitting should be considered as a higher level of seismic risk over the same reference period or, in a dual way, as a risk equal to new construction but over a smaller reference period (design working life). However, there is no specific guidance on the values to be adopted in the verification.

In scientific research, there are plenty of studies on the seismic retrofitting of framed structures but few studies on the verification of floors and their importance in seismic improvement and/or retrofitting strategies. This problem is relevant to both RC and masonry buildings. In the latter case, however, the presence of conservation constraints on some buildings of historical value prevents the choice of demolition by introducing an additional variable of fundamental importance in the intervention type selection. In the presence of historical constraints, buildings should have as their primary requirement the verification of safety for users or, if this is not possible, their downgrading or closure [25–27].

The purpose of the study is to define a model for evaluating the cost-effectiveness of interventions on residential RC buildings, considering the need to retrofit the existing floors. The most recurrent floor intervention techniques, generalized at a large territorial scale, have been considered. Retrofit interventions are consistent with vulnerability and fragility assessments commonly conducted in both research and professional settings. The evaluation of floor intervention costs is included in the building vulnerability assessment and cost–benefit analysis for a large-scale application. The considered typologies are derived from extensive studies conducted previously (e.g., [28,29]), expanded with experimental results and field surveys conducted over the past two decades. The main structural features are identified and recurrent floor patterns in existing buildings are analyzed. Finally, specific retrofit interventions are applied.

2. Existing RC Floors: Code and Typological Characterization

RC floors are a fundamental element in modern construction. They play a key role in the use, safety, structural stability, and design of buildings. First and foremost, floors must be able to withstand the expected gravity and live loads with acceptable stresses and strains. Based on the primary function, design loads include the weight of users, materials/equipment required for use, and non-structural parts needed for additional completion. In addition, floors may be called upon to perform structural functions with respect to horizontal actions (seismic and wind) that may act on a building. In fact, these actions depend on the in-plan regularity and elevation of the building, which is also conditioned by the in-plan stiffness and geometry of each floor.

Proper design and construction procedures ensure the long-term durability and safety of buildings. In the past, RC floors were made using different types and techniques, depending on the era of construction, local customs, and availability of prefabricated materials and products.

It should be emphasized that in existing buildings, the quality of concrete and steel reinforcement of floors is generally the same as that found in the buildings to which they belong. However, while in situ material testing of floors is practically non-existent and difficult to carry out, in many cases, partial prefabrication of floors may involve good and better-quality materials. In any case, the most significant problems are poor installation and maintenance. In the latter case, the poor resistance with respect to the actions required by modern standards is overlaid by the problem of the durability of floors over time, aggravated by the general lack of maintenance. In fact, modern regulations require regular maintenance operations to ensure strength and durability of structures. In the case of existing buildings, the exposure to aggressive environmental conditions (e.g., moisture and chemicals) has often induced significant damage to the structure of floors (see for example [30] and Figure 1). Although the effects of deterioration on reinforced concrete structures over time are well known, even some safety inspection methods often provide non-conservative results precisely because of the unimportance of floors [31].

Figure 1. Breakthrough of the floor: degradation of concrete, reinforcement, and brick block.

Finally, floors in existing buildings did not have any fire-resistant design; in contrast, this is a critical aspect in floor safety under the new regulations.

In the case of residential RC buildings, the sizing, design, and structural verification of floors are conducted simply and independently of the overall structural design of the building. These procedures have remained essentially unchanged for many years. Design objectives have generally been related to optimizing (if not minimizing) the size (particularly thickness) and quantity and arrangement of reinforcements. In fact, even historically, design involved simple methods to avoid total and partial collapses with respect to gravity and live loads alone.

Commonly, floor strength has been calculated based on permanent loads (structural and non-structural) and variable loads (dependent on use). The former may have varied over time in the non-structural part. In addition, the combination of actions provided in older standards results in load values significantly lower than those provided in modern standards.

Unfortunately, experimental activities devoted to the investigated types of floors are very poor. There are some experiments on different types and for different behavior problems. Several studies reported interesting analyses of building types and conditions similar to those analyzed here [27,32–34]. The focus is often related to the overall building behavior and the modeling procedures for the interaction between floors and vertical structural elements (in-plane stiffness, i.e., flexible floors) [35–37] or for particular loading conditions [37–41]. In this way, some interesting studies (for example, [42,43]) investigated the absence effects of adequate floor stiffness on the behavior of existing RC buildings.

Typological classification of existing buildings has been addressed only in a few cases [28,44], and construction details have often been neglected despite their significant relevance in the global behavior of buildings. By contrast, studies on floor rehabilitation interventions are significantly more widespread, although they generally refer to some plate floor types [45–48].

The assessment and retrofitting of existing buildings has been covered since the 1990s [49], evolving continuously in guidelines (for example, [50]), codes, and recommendations (e.g., [51]), as well as in scientific and professional publications. In Europe, the topic is addressed by Eurocode 8—Part 3 [52], namely the assessment and retrofitting of buildings [53]. EC8-3 is consistent with the first Italian code [54] and subsequent amendments (the last one in [24]). The methodological approach has been improved in the most recent technical regulations [24] and related guidelines.

In Italy, the use of RC structures, after their introduction in the late 1800s and early 1900s, was first regulated in a very old Italian code, i.e., Royal Decree No. 2229 of 1939 [55]. Royal Decree 2229/1939 was valid until 1972. Buildings falling within this historical context are considered herein. The reason for the specific interest in these buildings is twofold: (1) there were no specific limits in design regulations, but under the current regulations, they have now exhausted their required design working life (the current code requires the design life of new residential buildings to be 50 years), (2) the materials, design and construction techniques, poor maintenance, and consequent deterioration make these buildings particularly vulnerable. Therefore, for the purpose of risk mitigation, it is necessary to ask whether it is cost-effective to retrofit or demolish and rebuild older buildings.

Historical analysis, carried out on regulations, professional texts, and guidelines, indicates the original design philosophy, actions, and construction details. For example, RC buildings constructed under Royal Decree No. 2229 of 1939 had a structural concrete generally characterized by average strength values in the range of 120 to 225 kg/cm^2, i.e., significantly lower than those stipulated in later standards.

The indications of the regulations and guidelines regarding floor systems were very poor, and a typological classification was possible thanks to the study of a large database of original designs of residential RC buildings, from which some examples are given herein. Rib and block floor was the main type used. It consists of RC ribs built in place or prefabricated (even partially), with an infill made of blocks or various forms of permanent formwork. In general, all of these elements are covered by a cast-in-place concrete slab, containing specific upper reinforcement positioned to provide the required restraining moments. Some details of rib spacing, longitudinal length (e.g., span), and thickness are given below.

The effects of loads and their combinations were determined based on the linear-elastic behavior of the structure. For the safety verifications of resistance, no limit states were provided and considered as actual conceptual procedures. The design was based on the old

Allowable Stress Design (ASD) method that considers only the elastic strength of materials, limiting allowable stresses to a fraction (rather small, 40–50%) of the elastic limit. Loads were considered only as service loads, without applying amplifying factors because the combinations and partial safety factors foreseen in current limit state combinations were missing. Serviceability limit state verifications were not explicitly provided.

In residential buildings, RC floors play a key role. Collapse (even partial) of RC floors is a catastrophic event that can occur due to both ordinary actions and unusual loads. The main causes of RC floor collapse may include:

- Exceeding the expected load capacity due to actions beyond the design (original) ones.
- Structural deterioration over time due to exposure of materials to weathering, moisture, carbonation, corrosion of reinforcement, etc.
- Errors during design or construction of floors, such as inadequate amounts of reinforcement, inadequate thickness of concrete slabs, poor material characteristics, etc.
- Extraordinary actions, such as seismic events, fires, impacts, or blasts.

Thus, for existing buildings, it is necessary to analyze the original design and construction process and the actual state. Capacity can also be evaluated through load tests, i.e., tests performed to assess actual capacity. These tests are conducted to supplement and verify numerical evaluations [56]. Current regulations require verification of gravity and live loads whose importance is equal, and prior to verification of seismic loads [24]. Similarly to the seismic safety index, the safety index of vertical loads ($\zeta_{v,i}$) is defined as the ratio between the maximum value of the variable vertical overload supportable by the i^{th} part of the construction and the value of the variable vertical overload that would be used in the design of a new construction.

Currently, the analysis of stresses on floors uses extremely simple schemes, similar to those originally adopted. The increased values of external actions generally result in higher stresses than originally predicted.

3. Analysis of the Case Study

In the present study, RC buildings for residential use are considered. They are subdivided typologically according to the usual age classes also adopted in Italy by the National Institute of Statistics (ISTAT) to collect national housing data. This subdivision allows the results to be easily extended to a large spatial scale and compared with other studies. The considered buildings are grouped into two age classes or construction periods: (i) 1939–1960 and (ii) 1961–1971. According to the last ISTAT census data on residential buildings and housing (source: www.istat.it), most housing is in the second age class (Figure 2). In Figure 3, reinforcement details and dimensions of as-built RC floors in the investigated age classes are reported. These age classes are also commonly used in socio-economic surveys and in post-earthquake surveys.

The configurations analyzed in the study are described below. They belong to the rib and block floor type. Different configurations are analyzed, which differ from each other in terms of geometric characteristics. These configurations are obtained by varying the most recurrent structural schemes that can be deduced from the multitude of real situations investigated. In particular, the schematic characteristics of the considered sections are applied to different spans. They are shown in Figure 4 and are selected by combining the configurations most frequently encountered in real cases and code provisions. Concerning the structural materials, the average values of strengths provided by the regulations in force at the time were f_c = 16 MPa for concrete compressive strength and f_y = 320 MPa for the steel yielding stress.

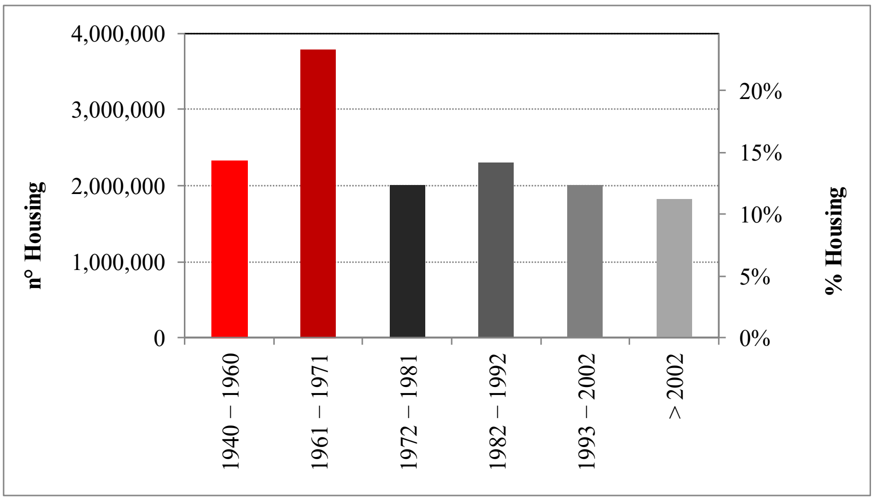

Figure 2. Age distribution of housing for existing reinforced concrete (RC) residential buildings.

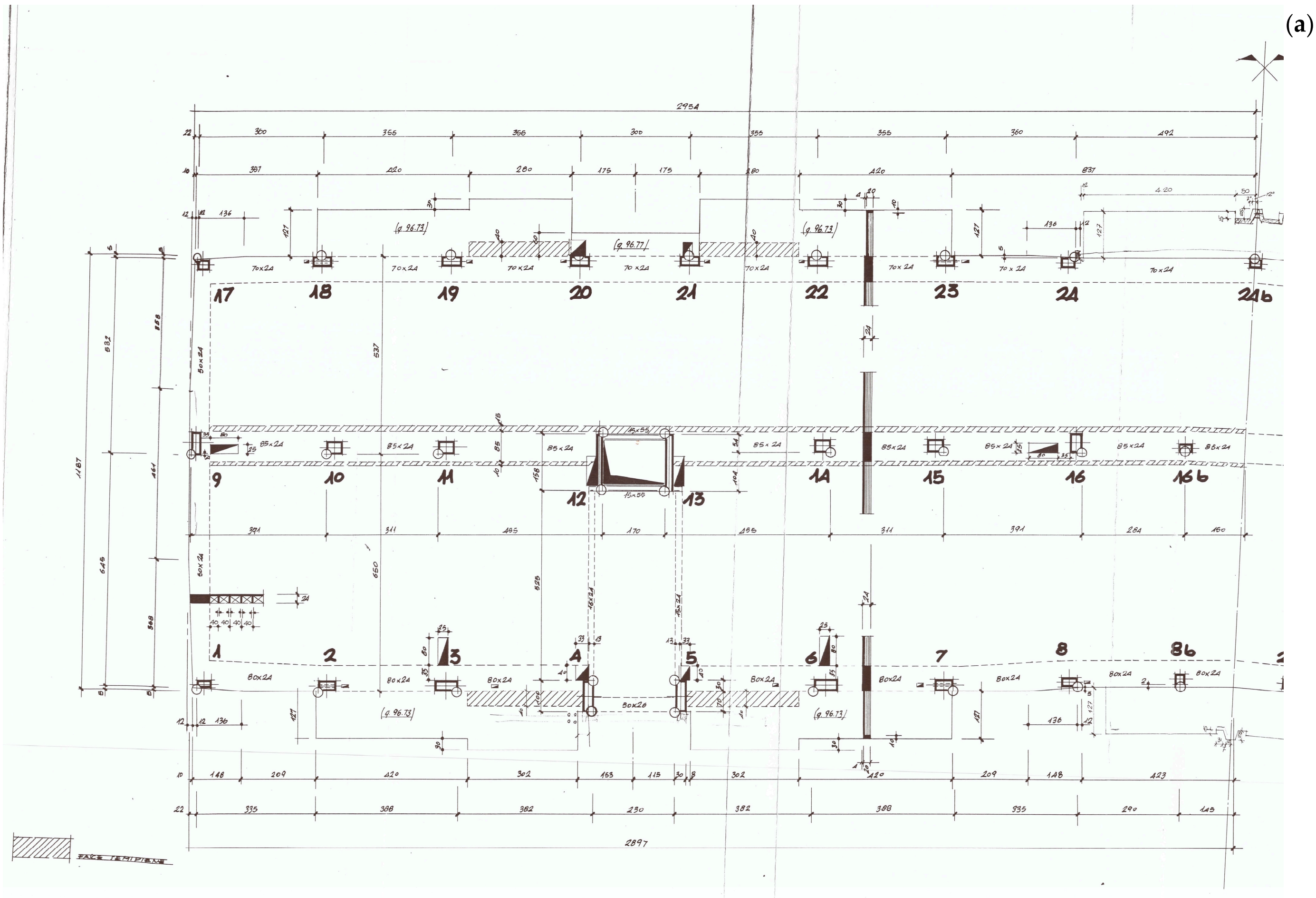

Figure 3. *Cont*.

(**b**)

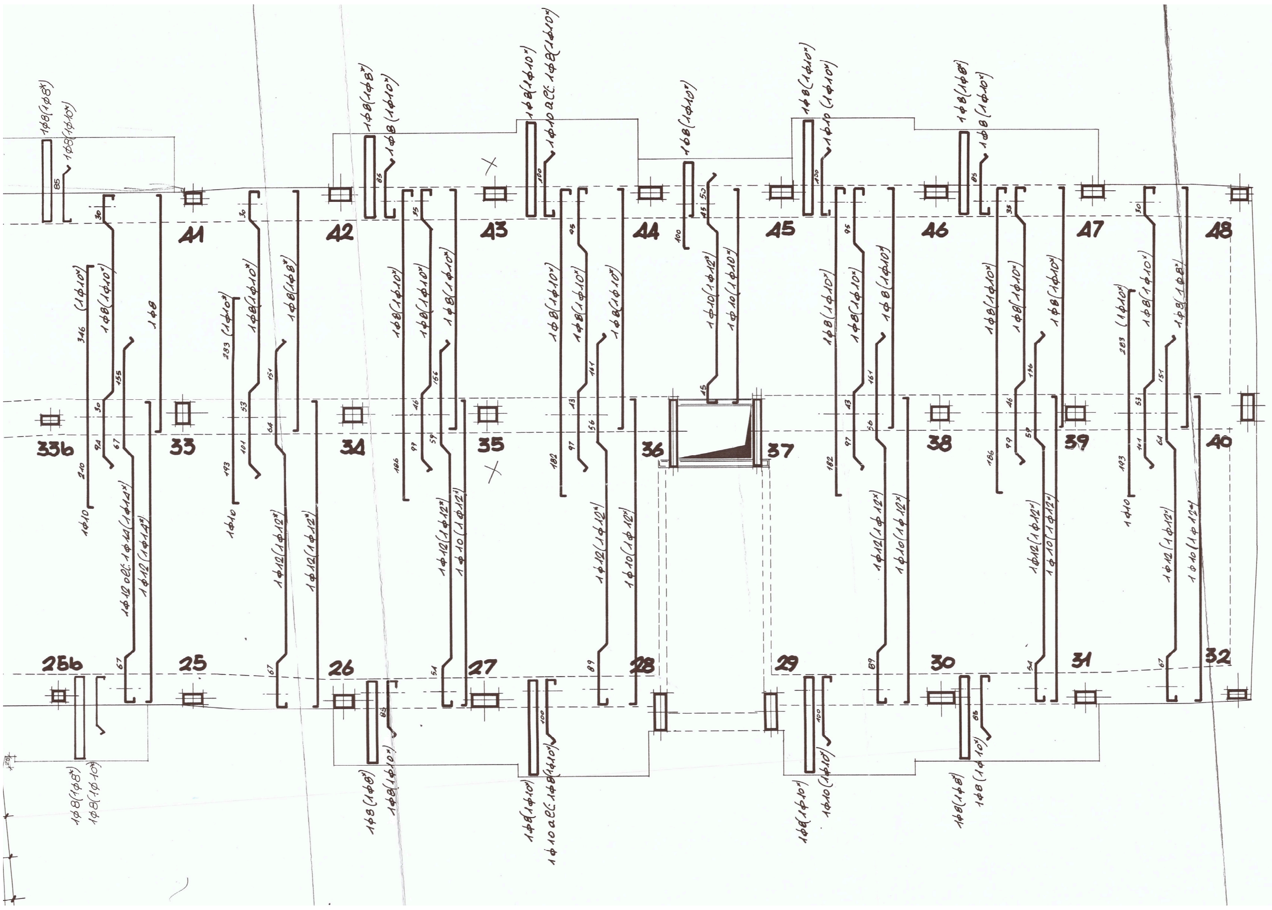

Figure 3. Example of floor configuration (**a**) and reinforcement details (**b**) of as-built RC floors in the investigated construction periods.

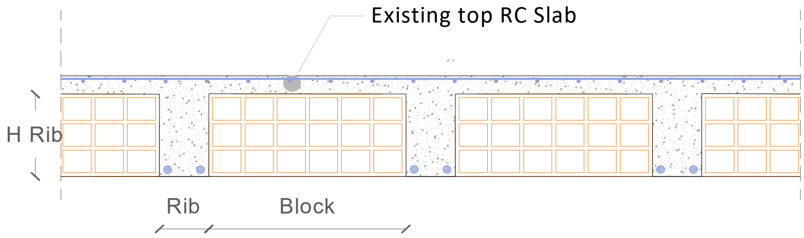

Figure 4. Qualitative and schematic characteristics of considered cases (positive moment cross section).

The structural scheme considered here is the classical two-span scheme, in which each span can vary from 3.00 to 5.00 m according to the span lengths (L1, L2) indicated in Table 1 and illustrated in Figure 5. To analyze the possible variations in geometries and construction details, 36 cross-section configurations (block, rib width and thickness; Table 1) and 6 longitudinal reinforcement quantities are investigated. This information is summarized in Table 1.

Table 1. Section properties of the investigated RC floors.

Span (L1, L2)	Block	Rib Width	H Rib	Reinforcement	Top Slab Thickness
[m]	[cm]	[cm]	[cm]	[n. bar; cm^2]	[cm]
3.0–3.5–4.0–4.5–5.0	30–35–40	5 10 12 14	16 18 20	[1 or 2 ϕ 10; 0.785–1.57] [1 or 2 ϕ 12; 1.13–2.26] [1 or 2 ϕ 14; 1.54–3.08]	4

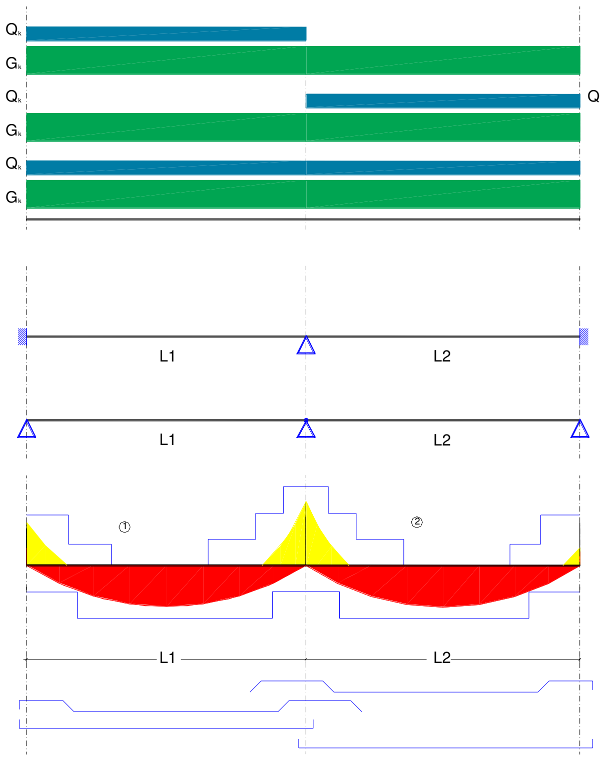

Figure 5. Multi-span schemes, load combinations, typological geometrical details of steel bars, and qualitative envelope diagram of acting (red and yellow) and resisting bending moments (stepwise trend).

To take into account the uncertainties in the strength of concrete, four average strength values (f_c) are considered for each construction period [57]. These values depend on the two ages of construction, respectively:

- Design/construction period 1939–1960: 6.8–12.5–15.0–20.1 MPa
- Design/construction period 1962–1971: 2.8–13.0–18.0–24.0 MPa.

Given the lower uncertainty in the strength of steel, a single average strength value of the reinforcement (f_y) is assigned to both construction periods since it has significantly less variable strength values than concrete [58]. Compatibly with the strength values of the regulations in force at the time and the most frequent values used in the original designs (Aq42), it is assumed equal to 320 MPa.

It is worth noting that the selected design/construction periods are identified considering the distribution of the existing building stock, which should represent a relevant portion of interest for assessment and intervention strategies. In addition, most of these buildings were designed and constructed in the absence of (or at least without compliance with) modern seismic provisions and, more importantly, with technologies and materials that are significantly less effective than current ones. Therefore, the analysis and verification of the investigated cases represent an important direction for a proper assessment of the existing heritage and an appropriate choice of both types of interventions and their prioritization needs.

In the usual applications of practitioners, the basic assumption for floors was their high in-plane stiffness and their ability to distribute forces on beams and vertical members. As a result, design practices were based on two simplified calculation schemes (continuous beams simply supported or fixed at their ends) to reduce and simplify computational efforts. In addition, different load combinations were considered to calculate the corresponding maximum values of shear and bending moment. These multi-span schemes, load combinations, geometrical details of steel bars, and qualitative diagram of acting and resisting bending moments are depicted in Figure 5.

Case studies are selected to investigate the role of verification of introduced vertical loads and the effects of variability in concrete characteristics. These case studies are a useful reference for professional applications.

With the adopted design and verification schemes and procedures, the strength values of the concrete are mainly conditioned for shear verification. The results of bending verification are summarized in Figure 6. The bending moment verification is mainly conditioned by the size of the slabs (bending stress), the thickness, and the reinforcement amount; different sizes of spans also play a key role. For the configurations with the longest spans and the smallest amount of reinforcement, the cross sections are not verified in bending.

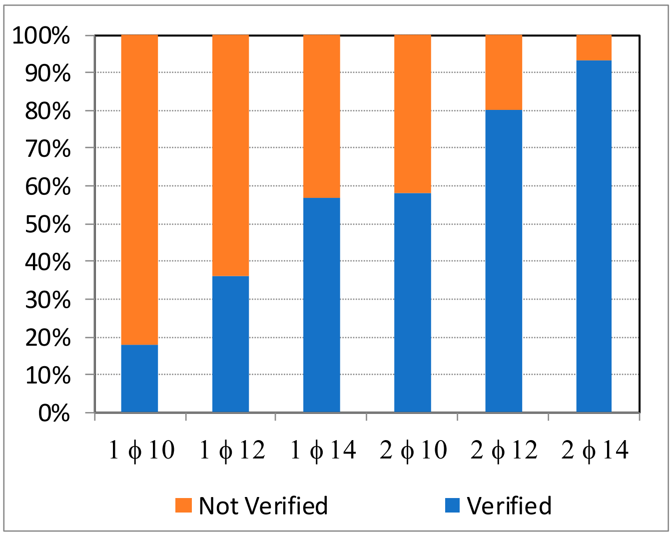

Figure 6. Bending verification results: blue and orange represent the percentage of verified and not verified cases, respectively.

Shear verification is always satisfied for the analyzed loads. In contrast, the bending verification is often not satisfied. In particular, the positive moment verification (in span) is often not satisfied. The performed verifications are little affected by the variability in concrete strength.

4. Selection and Resulting Cost Evaluation of Retrofit Interventions

All of the selected interventions aim at strengthening floors. For the selected interventions, the related costs are identified using ordinary working procedures based on unit costs, which are obtained from Italian price lists. Considering the reported schemes (Figures 4 and 5), a quantity approach is used to estimate the retrofit costs per square meter (EUR/m^2) of the investigated retrofit interventions. Based on the estimated cost of floors, the cost-effectiveness of a global intervention on buildings is estimated in order to identify technically effective and economically sustainable retrofit strategies.

For the purpose of the study, the main retrofit strategies (certainly not unique or exhaustive) are identified and applied to the typological classes of residential buildings considered and their possible state of deterioration. The intervention strategies are briefly described and unit costs are then defined.

Some typical intervention strategies are investigated: (1) interventions to increase the resistance of floors to positive and negative moments; (2) interventions to reduce the deformability of floors; and (3) interventions to eliminate the deterioration of reinforcement. These interventions are those generally needed in the types of buildings considered.

The analysis of interventions and their retrofit costs on RC floors requires a careful and detailed evaluation. More in detail, the retrofit costs can vary significantly depending on the extent of the intervention, the current condition of the floors, and the age of the structure.

Each retrofit intervention has specific cost items and associated unit costs derived from the DEI price list [59]. The latter provides a continuous update of unit prices and is commonly adopted by professionals. Costs include materials, labor, transportation, equipment, and overhead costs, as well as entrepreneurial profit.

Four types of retrofit interventions are considered: (i) reinforcement at the extrados of the existing slab, (ii) reinforcement of individual concrete beams with carbon fiber reinforced polymer (CFRP) composites, (iii) external post-tensioned cables (to counter vertical loads), and (iv) demolition and reconstruction of the floor (partial or total). The reference schemes for the first three intervention techniques are shown in Figure 7.

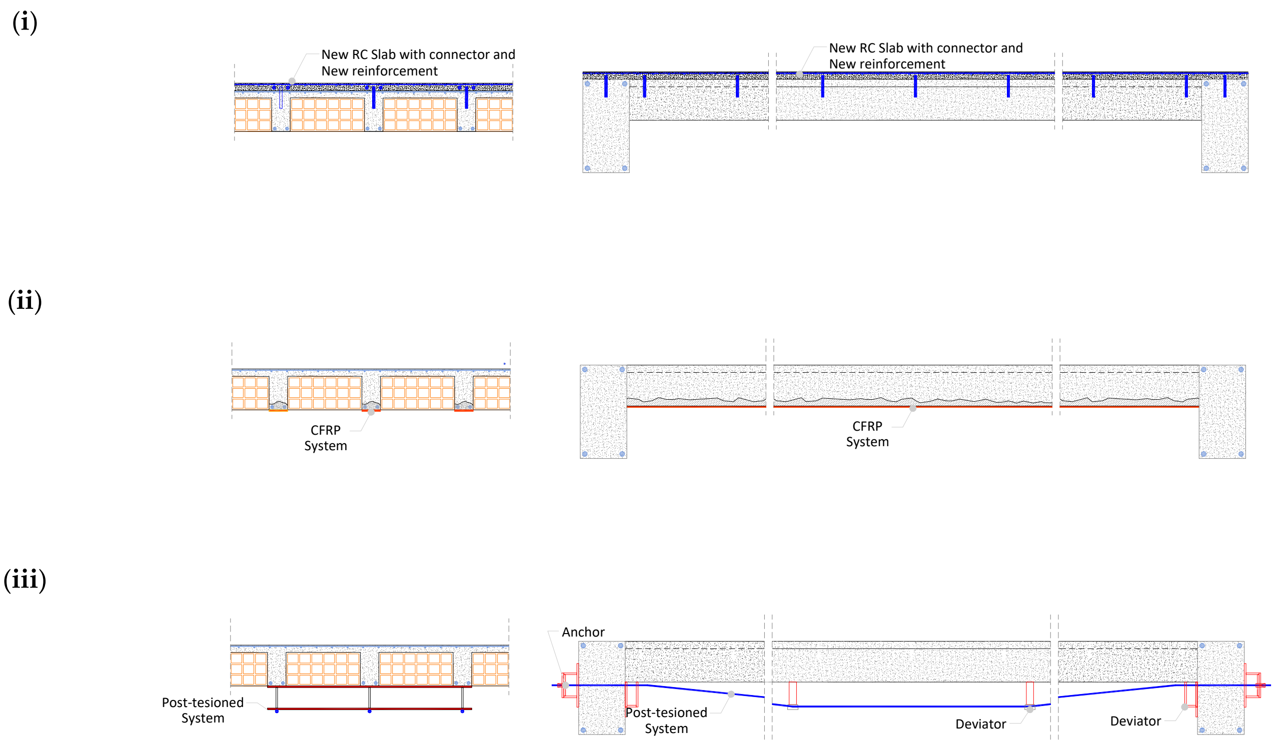

Figure 7. Considered retrofitting techniques: (i) reinforcement at the extrados of the existing slab, (ii) reinforcement of individual concrete beams with carbon fiber reinforced polymer (CFRP) composites, (iii) external post-tensioned cables (to counter vertical loads).

Lack of positive bending moment resistance is very common in the analyzed structures. In addition, the top concrete slab is often small and degraded. Reinforcement at the extrados of the floor is useful to eliminate the above critical issues. The intervention consists of increasing the strength by means of a cast-in-place concrete topping slab, which is perfectly connected to the existing slab by using specific connectors. It is capable of increasing strength and stiffness. However, the intervention is often extremely invasive and expensive due to the need to remove non-structural parts. Furthermore, it significantly increases seismic masses.

Lack of resistance to positive moments (usually in the central areas of the spans) can be achieved by intervening at the soffit, reinforcing individual concrete joists to increase their bending capacity. The most effective consolidation systems involve the use of high-strength and high-modulus unidirectional fibers fixed with impregnating and bonding epoxy resins. The procedure is often extremely invasive and expensive because of the need to prepare the concrete surface.

The lack of strength can be addressed with the application of external post-tensioned cables useful to counter vertical loads, with particular reference to permanent loads. This technology offers advantages due to the lower intrusiveness of the intervention on non-structural parts, but it does not allow the recovery of deficient situations with respect to dimensions (slab thickness) and degradation. External post-tensioning cable systems reduce the bending moments generated by gravity and live loads. The retrofit method is well established using both steel or CFRP cables [60–64]. However, the external post-tensioning system transfers the compressive force to the bearing point at the perimeter structural element. The transfer of compressive force must be carefully evaluated to avoid damage to the entire structure. The configuration is illustrated in Figure 7. It is based on reinforcement cables with dead- and live-end forged anchors. The desired effect is obtained by one or two intermediate deviators. Obviously, the configuration, number and location of deviators, as well as the type and location of anchors depend strongly on each individual case, depending on the size and type of structural and non-structural element, etc.

The technologies reported, although among the most widespread, are only the main technical possibilities of intervention. Obviously, each is characterized not only by the specific purposes of use, with relative advantages and disadvantages, but also by different implementation costs that can vary greatly on a case-by-case basis.

The average costs of interventions are evaluated parametrically from some real case studies. Application to real case studies is essential for the selected types of interventions. The latter have highly variable application modes and consequent costs depending on the size, and arrangement of structural and non-structural elements that may vary strongly on a case-by-case basis. Only intermediate floors are considered in the cost analysis. Roof floors are excluded: their configurations, interventions, and costs can be highly variable.

Intervention (i) is applied to the extrados of the floors and is simulated in the selected case studies. It involves the removal of existing interior infill, flooring, electrical and heating systems, and fixtures, followed by their complete rehabilitation.

Intervention (ii) is applied to the bottom of the floor. The simulation involves the removal of finishing plaster and existing installations (at least the electrical system); therefore, restoration includes painting. The actual (or net) structural area of intervention is considered in the metric calculation.

Intervention (iii) is applied to the intrados of the floors. The simulation includes the placement of cables, deviators, and anchoring devices; the non-structural parts affected by the intervention are extremely limited. The deviators are mounted between the end anchors. They are simple threaded steel bolts connected to a base plate and bent plate. Several details (such as low-friction contact surface, bend radius of the bent plate, etc.) must be designed on a case-by-case approach.

Intervention (iv), demolition and reconstruction, is computed in a relatively simple way, also considering the cost of rubble disposal; the most uncertain and technically relevant part of the costs is the connection to existing structures.

The need for staircase retrofitting is not considered here. Although there is substantial variability in the characteristics of existing concrete floors, the analysis represents a wide range of types.

For each type of intervention, the sum of the cost items defines the total calculated cost. In addition, overhead and entrepreneurial profits are considered. In Table 2, the total costs (EUR) are summarized per square meter (EUR/m^2). It should be emphasized that the estimated total costs are indicative and cannot take into account all possible local conditions such as: reconstruction or replacement of structures, demolition and reconstruction of partitions, etc.

Table 2. Average unit costs of individual retrofit interventions (EUR/m^2).

	Intervention Techniques	Min	Med	Max
(i)	**Reinforcement at the extrados**	220	280	680
(ii)	**Reinforcement with CFRP**	480	540	620
(iii)	**External post-tensioned cables**	180	250	520
(iv)	**Demolition and reconstruction**	380	440	700

5. Discussion

In practical applications, costs could significantly increase depending on the multitude of specific problems and operational and construction requirements encountered in each case. In addition, there may be a need to work together on the soffit intrados and extrados, thus increasing the costs of the interventions. In particular, in demolition and reconstruction interventions, the costs related to the construction of new structures must also be considered, as well as the operations of connecting the new slab with the existing load-bearing structure (an operation that is complex and highly variable from case to case). Consequently, this type of intervention, especially if widespread, can reach much higher costs, on the order of EUR 700/m^2.

These costs are normalized to the average cost of new construction and the maximum cost of intervention [65]. In addition, property market value data are considered to assess the propensity of residential building owners to undertake retrofit actions. These data may condition the propensity to intervene [66]. The importance of evaluation in maintenance intervention choices should be highlighted.

Figure 8 graphically illustrates the variation in the performance capacity of a generic functional element of the building in relation to different maintenance intervention hypotheses, also specifying, based on an increase in the required quality standard (e.g., due to a change in regulations), the difference between the physical lifespan (in the absence of maintenance), the functional lifespan (service life), and the economic useful life.

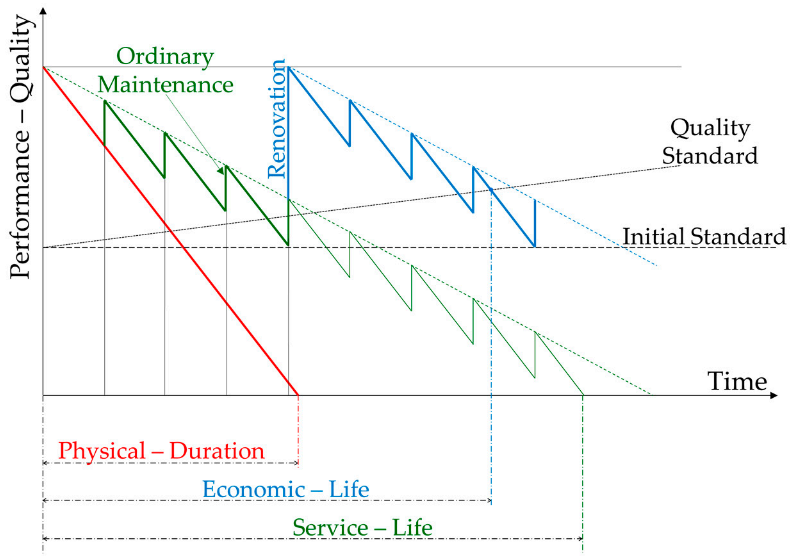

Figure 8. Variation in the performance capacity of the functional element of the building in relation to different intervention hypotheses.

Figure 8 focuses on aspects related to technical efficiency but does not consider that the economic useful life may be influenced not only by the demand for greater performance capacity but also by the dynamics of market values (economic evaluation).

The degradation processes of parts of the real estate unit are reflected in a loss of the property's profitability and thus its value. The decline in the performance of a building has a more or less direct relationship with its income-generating capacity, depending on whether the building itself generates income (residence, hotel, etc.) or if what is contained in the building generates income (industry, commercial building, school, hospital, etc.). The loss of income-generating capacity can be countered with actions to restore performance through maintenance interventions, which are associated with costs. The cost-effectiveness of the intervention should be evaluated by comparing the maintenance costs with the performance recovery that follows in terms of profitability and therefore value. The value of the building is in turn linked to the overall dynamics of property values or to macro- and micro-exogenous factors, the latter resulting, for example, from contextual transformation policies (see Figure 9).

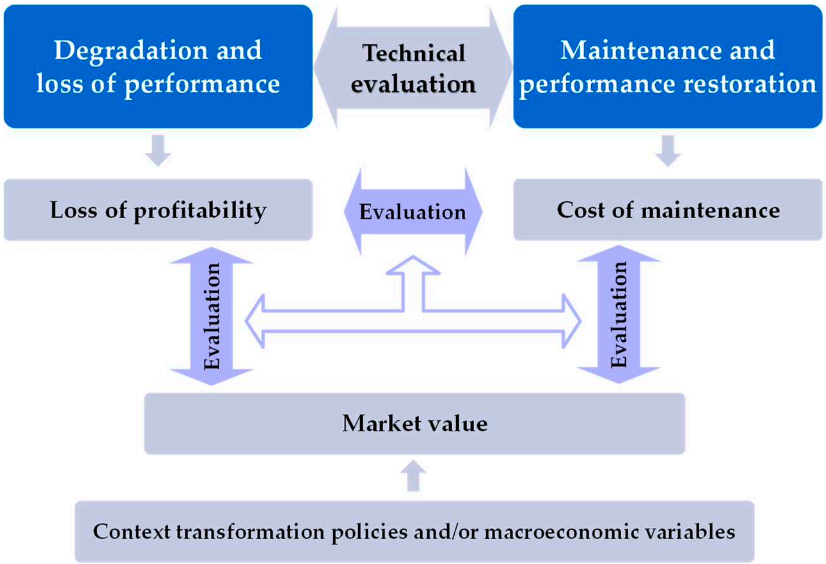

Figure 9. Framework highlighting the importance of technical and economic evaluation in the selection of maintenance actions.

Therefore, it is worthwhile to invest resources in the redevelopment of the real estate unit or building if the increase in value is sufficient to cover the expenses incurred and ensure a "fair" profit in case of sale. A comparison must be made between the value before the restructuring (V_1), the value after the restructuring (V_2), and the expenses incurred (S_p). It must be verified as follows:

$$V_1 + S_p < V_2. \quad (1)$$

The economic sustainability of the intervention is confirmed when there is a strong complementary relationship between the element to be redeveloped and the whole. There is no doubt that in the case of the floor slab, like any structural element, complementarity with the remaining functional elements of the building (systems and finishes) is perfect. The building could not survive without the functionality of all these elements, and the service life of the entire building coincides with the shortest among the service lives that characterize its structural parts (foundations, superstructure, floor slabs).

If, however, the economic sustainability of the maintenance intervention is not verified, it means that the depreciation suffered by the part of the building to be redeveloped is now considered irreversible. Depreciation is indeed irreversible if the maintenance intervention has a cost that exceeds the increase in market value that the same intervention generates.

The cost-effectiveness of an intervention on floors should be compared with the replacement cost of the building. Existing buildings constructed 20, 30, or 40 years ago still have a residual service life that could be affected by the execution of this type of intervention. The choice depends on the cost of retrofit solutions but also on the damage caused by the inability to use the building (risk of slab collapse), the age of the building, and the boundary conditions.

It should be noted that the cost-effectiveness of a retrofit intervention on an existing building must be evaluated in comparison with the direct benefit generated by this intervention measure, referring also to other alternatives. One of these is, for example, the demolition and reconstruction of the building [20]. The buildings analyzed in this study are considered as having zero residual life, following the guidance of the new regulations. In these cases, it is necessary to develop specific value curves for the replacement cost of the building minus depreciation as a function of age.

Moreover, often the proposed and available seismic retrofitting solutions are still questionable and do not consider floors, particularly for the buildings under investigation in this study. Even more, combined seismic and energy retrofitting [13–23] is a very recent topic of research and application, and there are only a few studies in this regard. Certainly, costs should be evaluated by considering the environmental impact as well. However, no study has yet considered all of these aspects together, and the present study highlights how all aspects can be conditioned on the safety verifications of resistance of floors and the consequent convenience of intervening. In fact, as important as the environmental aspects are, recent Italian experiences have shown that there are still very significant financial problems. In any case, no intervention (environmental, energy, etc.) should be allowed without a proper assessment of the resistance of the floors and the consequent retrofitting.

6. Conclusions

This study provides methods and proposals to establish general strategies for the evaluation and retrofitting of existing buildings. It is applicable to the evaluation and possible retrofitting of old existing RC buildings, whose original design, construction, and maintenance status are deficient compared to current design standards. As a result, the study could be very useful for professionals, public and private authorities managing large building stocks, insurance companies, owners, and all those interested in evaluating the possible retrofitting of a building.

Models for risk analysis commonly available at the national and regional scales (macroscale) generally refer to poor data (e.g., ISTAT data: building material, period of construction, and number of floors). On this basis, retrofit cost models may not be reliable for correct choices by decision makers. In addition, retrofit cost models do not consider the possibility of having to intervene directly on floors. In this case, the high cost conditions the intervention strategy.

This conditioning strongly depends on the spatial context and the market value of the buildings considered. Therefore, in order to obtain a cost model suitable for analysis on a regional or national scale, a simplified cost model is presented by identifying representative unit costs of retrofit for floors in residential RC buildings that are grouped into two age classes. The buildings belonging to these two classes are generally the most vulnerable and generally have low market values and high intervention costs.

The study analyzes the performance of the floors in the considered age classes and implements four retrofit interventions commonly used to address their structural deficiencies in order to estimate the total cost of each intervention. A comparative approach of unit costs within each macro class of buildings is implemented, resulting in cost estimates.

The following are some essential points that emerged from the study:

- shear checks are mainly conditioned by the strength values of the concrete, while the bending moment checks are mainly influenced by the size of the slabs and the thickness and quantity of reinforcement. Positive moment checks (in span) are often not satisfied without intervention;
- the cost-effectiveness evaluation of an intervention on existing buildings rather than their demolition and reconstruction should go through a technical-economic assessment that also includes the performance of floors. Consequently, the retrofit intervention should be tailored to the structural criticalities found, trying to minimize costs, disturbance, and increase in mass;

- in many cases, the retrofit intervention implementation may be considered uneconomical and therefore highly unlikely due to the high retrofit cost compared to the market value of the considered building. In such cases, since safety of vertical loads is not guaranteed, the buildings should be decommissioned;
- particularly for the 1960s and 1970s types, numerical analyses and intervention strategies should always be supplemented with floor load tests.

As a preliminary rough estimate, thanks to the different uncertainties analyzed in the present study, the obtained results could also be extended to other residential buildings having similar characteristics in terms of reinforcement details, configurations, geometrical dimensions and material strength values (concrete and steel). However, the characteristics of more recent residential buildings (from the 1970s onward) may be completely different.

Finally, for each retrofit intervention, the time spent during the repair process, the post-repair duration, and the environmental impact are neglected. These aspects will be further improved in future research. Moreover, the market values (and their distributions) of the building types considered in this study will be further analyzed and explored.

Author Contributions: Conceptualization, M.V. and B.M.; methodology, M.V.; validation, M.V., A.A., F.P.D.G. and B.M.; formal analysis, M.V.; investigation, M.V. and A.A.; resources, M.V. and B.M.; data curation, M.V. and A.A.; writing—original draft preparation, M.V.; writing—review and editing, M.V., A.A., F.P.D.G. and B.M.; visualization, M.V., A.A., F.P.D.G. and B.M.; supervision, M.V. and B.M.; funding acquisition, M.V. and B.M. All authors have read and agreed to the published version of the manuscript.

Funding: The current study was developed within the current research P.R.I.N. Project 2022: "INSPIRE—Improving Nature-Smart Policies through Innovative Resilient Evaluations", Grant number: 2022J7RWNF.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Caterino, N.; Cosenza, E. A multi-criteria approach for selecting the seismic retrofit intervention for an existing structure accounting for expected losses and tax incentives in Italy. *Eng. Struct.* **2018**, *174*, 840–850. [CrossRef]
2. Anelli, A.; Santa-Cruz, S.; Vona, M.; Tarque, N.; Laterza, M. A proactive and resilient seismic risk mitigation strategy for existing school buildings. *Struct. Infrastruct. Eng.* **2019**, *15*, 137–151. [CrossRef]
3. Anelli, A.; Vona, M.; Santa-Cruz, S. Comparison of different intervention options for massive seismic upgrading of essential facilities. *Buildings* **2020**, *10*, 125. [CrossRef]
4. Vona, M.; Anelli, A.; Mastroberti, M.; Murgante, B.; Santa-Cruz, S. Prioritization strategies to reduce the seismic risk of the public and strategic buildings. *Disaster Adv.* **2017**, *10*, 1–15.
5. Vona, M.; Flora, A.; Carlucci, E.; Foscolo, E. Seismic retrofitting resilience-based for strategic RC buildings. *Buildings* **2021**, *11*, 111. [CrossRef]
6. Hamzehkolaei, N.S.; Alizamir, M. Performance Evaluation of Machine Learning Algorithms for Seismic Retrofit Cost Estimation Using Structural Parameters. *J. Soft Comput. Civ. Eng.* **2021**, *5*, 32–57. [CrossRef]
7. United Nations Environment Programme. *Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector*; United Nations Environment Programme: Nairobi, Kenya, 2020.
8. European Commission. *The European Green Deal—Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions*; European Commission: Brussels, Belgium, 2019.
9. Secretary of State. *The Energy Efficiency (Building Renovation and Reporting) (Amendment) Regulations*; TSO (The Stationery Office): London, UK, 2020.
10. The White House. *FACT SHEET: Biden Administration Accelerates Efforts to Create Jobs Making American Buildings More Affordable, Cleaner, and Resilient*; The White House: Washington, DC, USA, 2021.
11. Huo, T.; Cai, W.; Ren, H.; Feng, W.; Zhu, M.; Lang, N.; Gao, J. China's building stock estimation and energy intensity analysis. *J. Clean. Prod.* **2019**, *207*, 801–813. [CrossRef]

12. IEA (International Energy Agency). Policy Database' IEA. Available online: https://www.iea.org/policies (accessed on 9 May 2024).
13. Pohoryles, D.A.; Bournas, D.A.; Da Porto, F.; Santarsiero, G.; Triantafillou, T. Integrated seismic and energy retrofitting of existing buildings: A state-of-the-art review. *J. Build. Eng.* **2022**, *61*, 105274. [CrossRef]
14. Dolce, M.; Prota, A.; Borzi, B.; da Porto, F.; Lagomarsino, S.; Magenes, G.; Moroni, C.; Penna, A.; Polese, M.; Speranza, E.; et al. Seismic risk assessment of residential buildings in Italy. *Bull. Earthq. Eng.* **2021**, *19*, 2999–3032. [CrossRef]
15. Di Ludovico, M.; Prota, A.; Moroni, C.; Manfredi, G.; Dolce, M. Reconstruction process of damaged residential buildings outside historical centres after the L'Aquila earthquake: Part II "heavy damage" reconstruction. *Bull. Earthq. Eng.* **2017**, *15*, 693–729. [CrossRef]
16. Di Ludovico, M.; Prota, A.; Moroni, C.; Manfredi, G.; Dolce, M. Reconstruction process of damaged residential buildings outside historical centres after the L'Aquila earthquake: Part I "light damage" reconstruction. *Bull. Earthq. Eng.* **2017**, *15*, 667–692. [CrossRef]
17. Dolce, M. Emergency and Post-emergency Management of the Abruzzi Earthquake. In *Earthquake Engineering in Europe Geotechnical, Geological, and Earthquake Engineering*; Garevski, M., Ansal, A., Eds.; Springer: Dordrecht, The Netherlands, 2010; pp. 463–494. [CrossRef]
18. Di Ludovico, M.; Giuseppina, L.; Andrea, D.M.; Gaetano, P. Relationships between empirical damage and direct/indirect costs for the assessment of seismic loss scenarios. *Bull. Earthq. Eng.* **2021**, *20*, 229–254. [CrossRef]
19. Ufficio Speciale per la Ricostruzione dei Comuni del Cratere. *Libro Bianco sulla Ricostruzione Privata dei Centri Storici nei Comuni Colpiti dal Sisma Abruzzo 2009*; Di Ludovico, M., Dolce, M., Prota, A., Eds.; Ufficio Speciale per la Ricostruzione dei Comuni del Cratere: Foggia, Italy, 2022.
20. *Ministerial Decree 58/2017; Sisma Bonus—Linee Guida per la Classificazione del Rischio Sismico delle Costruzioni Nonché le Modalità per L'attestazione, da Parte di Professionisti Abilitati, Dell'efficacia Degli Interventi Effettuati*; Ministero delle Infrastrutture e dei Trasporti: Rome, Italy, 2017. (In Italian)
21. Ministerial Decree No. 24/2020. Available online: https://www.mit.gov.it/normativa/decreto-ministeriale-numero-24-del-0901 2020 (accessed on 2 January 2023).
22. Ministero delle Infrastrutture e dei Trasporti. *Circolare 21 Gennaio 2019, n. 7 C.S.LL.PP. Istruzioni per L'applicazione dell'«Aggiornamento delle "Norme Tecniche per le Costruzioni"» di Cui al Decreto Ministeriale 17 Gennaio 2018. Circolare n. 7 C.S.LL.PP. Suppl. Or. G.U., n. 35 del 11 Febbraio 2019—Serie Generale*; Ministero delle Infrastrutture e dei Trasporti: Roma, Italy, 2019. (In Italian)
23. Mastroberti, M.; Bournas, D.; Vona, M.; Manganelli, B.; Palermo, V. Combined seismic plus energy retrofitting for the existing RC buildings: Economic feasibility and environmental benefits. In Proceedings of the 16th European Conference on Earthquake Engineering (16ECEE), Thessaloniki, Greece, 18–21 June 2018.
24. *NTC 2018*; Decreto del Ministro delle Infrastrutture e dei Trasporti del 17 Gennaio 2018, Nuove Norme Tecniche per le Costruzioni. Suppl. Or. G.U., n. 42 del 20 Febbraio 2018—Serie Generale. Ministero delle Infrastrutture e dei Trasporti: Roma, Italy. (In Italian)
25. Vona, M.; Manganelli, B. The Historical and Cultural Value of RC Constructions and the Main Critical Issues for Rehabilitation. *Infrastructures* **2022**, *7*, 35. [CrossRef]
26. Sisti, R.; Di Ludovico, M.; Borri, A.; Prota, A. Seismic performance of strengthened masonry structures: Actual behaviour of buildings in Norcia and Campi Alto during the 2016 Central Italy seismic sequence. *Bull. Earthq. Eng.* **2022**, *20*, 321–348. [CrossRef]
27. Dmochowski, G.; Berkowski, P.; Szolomicki, J.; Minch, M. Reinforced concrete floors in historic buildings from the beginning and the middle of the 20th century—Examples of structural strengthening in the process of revitalization. In Proceedings of the 12th International Conference on Structural Analysis of Historical Constructions SAHC 2020, Barcelona, Spain, 16–18 September 2020; Roca, L.P., Molins, C., Eds.; Scipedia: Barcelona, Spain.
28. Manfredi, G.; Masi, A.; Pinho, R.; Verderame, G.M.; Vona, M. *Valutazione di Edifici Esistenti in Cemento Armato, Collana di Manuali di Progettazione Antisismica*; IUSS Press: Pavia, Italy, 2007; Volume 5, ISBN 978-88-6198-013-6.
29. Vona, M. Fragility curves of existing RC buildings based on specific structural performance levels. *Open J. Civ. Eng.* **2014**, *4*, 120–134. [CrossRef]
30. Porco, G.; Forestieri, F.; Scattarreggia, M. Numerical treatment and interpretation of the NDT data for the check on floors. In Proceedings of the Italian Concrete Conference, ICC 2022, Napoli, Italy, 12–15 October 2022.
31. Cho, H.-C.; Lee, S.-H.; Choi, S.-H.; Kang, W.-H.; Kim, K.S. Structural Safety Inspection of Reinforced Concrete Structures Considering Failure Probabilities of Structural Members. *Int. J. Concr. Struct. Mater.* **2023**, *17*, 12. [CrossRef]
32. Nguyen, M.C.T.; Pham, P.T. An investigation on the behaviour and stiffness of reinforced concrete slabs subjected to torsion. *IOP Conf. Ser. Mater. Sci. Eng.* **2017**, *164*, 012017. [CrossRef]
33. Masoudi, M.; Khajevand, S. Revisiting flexural overstrength in RC beam-and-slab floor systems for seismic design and evaluation. *Bull. Earthq. Eng.* **2020**, *18*, 5309–5341. [CrossRef]
34. Manoukas, G.E.; Karayannis, C.G. Seismic Interaction between Multistory Pilotis RC Frames and Shorter Structures with Different Story Levels—Floor-to-Column Pounding. *CivilEng* **2023**, *4*, 618–637. [CrossRef]
35. Pecce, M.R.; Ceroni, F.; Maddaloni, G. In-plane deformability of RC floors: Assessment of the main parameters and influence on dynamic behaviour. *Bull. Earthq. Eng.* **2019**, *17*, 297–311. [CrossRef]

36. Frappa, G.; Pitacco, I.; Baldassi, S.; Pauletta, M. Methods to Reproduce In-Plane Deformability of Orthotropic Floors in the Finite Element Models of Buildings. *Appl. Sci.* **2023**, *13*, 6733. [CrossRef]
37. Saler, E.; Gattesco, N.; da Porto, F. A new combined approach to prioritise seismic retrofit interventions on stocks of r.c. school buildings. *Int. J. Disaster Risk Reduct.* **2023**, *93*, 103767. [CrossRef]
38. Kristiawan, S.; Supriyadi, A.; Pradana, D.R.; Azhim, M.R.N. Flexural behaviour of one-way patched reinforced concrete (RC) slab under concentrated load. *Asian J. Civ. Eng.* **2018**, *19*, 157–164. [CrossRef]
39. Pham, T.B.; Mai, V.-C.; Nguyen, V.T.; Dao, C.-B. Numerical investigation of the punching shear resistance capacity of reinforced concrete slab. In *IOP Conference Series: Materials Science and Engineering, Proceedings of the 4th International Conference on Transportation Infrastructure and Sustainable Development (TISDIC-2023), Danang, Vietnam, 26–28 August 2023*; IOP Publishing: Bristol, UK, 2023; Volume 1289.
40. Oymanli, S.A.; Avşar, Ö. Protection of Reinforced Concrete Columns from Pounding-Induced Effects in Adjacent Buildings. *Turk. J. Civ. Eng.* **2024**, *35*, 47–70. [CrossRef]
41. Bakardzhiev, S. Study of the behavior of a experimental reinforced concrete slab at different stages of loading from the production of the reinforced concrete slab over it. *IOP Conf. Ser. Mater. Sci. Eng.* **2023**, *1276*, 012024. [CrossRef]
42. Ruggieri, S.; Porco, F.; Uva, G. A numerical procedure for modeling the floor deformability in seismic analysis of existing RC buildings. *J. Build. Eng.* **2018**, *19*, 273–284. [CrossRef]
43. Ruggieri, S.; Porco, F.; Uva, G. A practical approach for estimating the floor deformability in existing RC buildings: Evaluation of the effects in the structural response and seismic fragility. *Bull. Earthq. Eng.* **2020**, *18*, 2083–2113. [CrossRef]
44. Xavier, V.; Couto, R.; Monteiro, R.; Castro, J.M.; Bento, R. Detailed Structural Characterization of Existing RC Buildings for Seismic Exposure Modelling of the Lisbon Area. *Buildings* **2022**, *12*, 642. [CrossRef]
45. Badini, L.; Ott, S.; Aondio, P.; Winter, S. Seismic strengthening of existing RC buildings with external cross-laminated timber (CLT) walls hosting an integrated energetic and architectural renovation. *Bull. Earthq. Eng.* **2022**, *20*, 5963–6006. [CrossRef]
46. Nguyen, H.Q.; Han, T.H.; Park, J.K.; Kim, J.J. A Design Process for Preventing Brittle Failure in Strengthening RC Slabs with Hybrid FRP-HPC Retrofit Systems. *Materials* **2023**, *16*, 755. [CrossRef]
47. Buda, R.; Bedon, C.; Pucinotti, R. Retrofit of Existing Reinforced Concrete (RC) Buildings: Steel vs. RC Exoskeletons. *Appl. Sci.* **2022**, *12*, 11511. [CrossRef]
48. Li, B.; Li, Z.; Chen, Z.; Yang, Z.; Zhang, Y. Experimental Study on the Structural Performance of Reinforced Truss Concrete Composite Slabs during and after Fire. *Buildings* **2023**, *13*, 1615. [CrossRef]
49. *ATC-40*; Seismic Evaluation and Retrofit of Concrete Buildings. Applied Technology Council: California, CA, USA, 1996; Report No. SSC 96-01.
50. Federal Emergency Management Agency (FEMA). *FEMA 356—Prestandard and Commentary for the Seismic Rehabilitation of Buildings*; Federal Emergency Management Agency: Washington, DC, USA, 2000.
51. New Zealand Society for Earthquake Engineering (NZSEE). *Assessment and Improvement of the Structural Performance of Buildings in Earthquakes*; New Zealand Society for Earthquake Engineering (NZSEE): Wellington, New Zealand, 2006.
52. *Standard EN 1998-3-2005*; Comité Européen de Normalisation, CEN. European Eurocode 8: Design of Structures for Earthquake Resistance—Part 3: Assessment and Retrofitting of Buildings. European Committee for Standardization: Brussels, Belgium, 2005.
53. *EUR 27128*; European Commission Joint Research Centre. New European Technical Rules for the Assessment and Retrofitting of Existing Structures. Publications Office of the European Union: Luxembourg, 2015. [CrossRef]
54. *OPCM 3274*; Ordinanza del Presidente del Consiglio dei Ministri del 20 marzo 2003 Primi Elementi in Materia di Criteri Generali per la Classificazione Sismica del Territorio Nazionale e di Normative Tecniche per le Costruzioni in Zona Sismica. Civil Protection Department: Rome, Italy, 2003; G.U. del 8/5/2003.
55. *Regio Decreto 16/11/1939 n. 2229*; Norme per la Esecuzione delle Opere in Conglomerato Cementizio Semplice ed Armato. G.U. n. 92 del 18/4/1940.
56. Saleem, M.A.; Abbas, S.; Nehdi, M.L. Assessment of reinforced concrete slabs using in-situ load testing: A case study. *J. Build. Eng.* **2019**, *25*, 100844. [CrossRef]
57. Vona, M. Characterization of In Situ Concrete of Existing RC Constructions. *Materials* **2022**, *15*, 5549. [CrossRef] [PubMed]
58. Verderame, G.M.; Stella, A.; Cosenza, E. Le proprietà meccaniche degli acciai impiegati nelle strutture in c.a. realizzate negli anni '60. In Proceedings of the X Congresso Nazionale "L'ingegneria Sismica in Italia", Matera, Italy, 9–13 September 2001.
59. DEI—Tipografia del Genio Civile. *Prezzi informativi dell'edilizia. Materiali ed opere Compiute. Recupero, Ristrutturazione, Manutenzione*. DEI—Tipografia del Genio Civile, Quine S.r.l.: Milano, Italy, Aprile 2020. Available online: https://www.build.it/prezzari/ (accessed on 9 May 2024).
60. Lee, M.J.; Lee, K. Performance and Cost Effectiveness Analysis of the Active External Post Tensioning System. *J. Asian Archit. Build. Eng.* **2012**, *11*, 139–146. [CrossRef]
61. Gao, D.; Fang, D.; You, P.; Chen, G.; Tang, J. Flexural behavior of reinforced concrete one-way slabs strengthened via external post-tensioned FRP tendons. *Eng. Struct.* **2020**, *216*, 110718. [CrossRef]
62. Matta, F.; Nanni, A.; Abdelrazaq, A.; Gremel, D.; Koch, R. Externally post-tensioned carbon FRP bar system for deflection control. *Constr. Build. Mater.* **2009**, *23*, 1628–1639. [CrossRef]
63. Mostakhdemin Hosseini, M.R.; Dias, S.J.E.; Barros, J.A.O. Behavior of one-way RC slabs flexurally strengthened with prestressed NSM CFRP laminates—Assessment of influencing parameters. *Compos. Struct.* **2020**, *245*, 112259. [CrossRef]

64. Sahib, M.Q.A.; Aghayari, R.; Moradi, M.J.; Roudsari, M.T. Experimental Investigation on the Rehabilitation of RC Flat Slabs Using CFRP Sheets to Enhance Punching Shear Capacity. *Buildings* **2024**, *14*, 153. [CrossRef]
65. Vona, M.; Anelli, A.; Harabaglia, P. Seismic resilience study for a prioritization plan in a high seismic hazard area. In *LNCS, Proceedings of the International Conference on Computational Science and Its Applications Notification, Hanoi, Vietnam, 1–4 July 2024*; Springer: Berlin/Heidelberg, Germany.
66. Manganelli, B.; Vona, M.; De Paola, P. Evaluating the cost and benefits of earthquake protection of buildings. *J. Eur. Real Estate Res.* **2018**, *11*, 263–278. [CrossRef]