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Holistic Assessment for Social Housing Retrofitting: Integrating Seismic, Energy, and Social Aspects in the REHOUSE Project

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Abstract: There are many existing buildings for which seismic rehabilitation interventions are required, especially in earthquake-prone areas like Italy. At the same time, the huge energy cost increase in Europe highlights the need for sustainable techniques that are able to increase the energy efficiency of buildings. These issues are even more significant for weak social groups living in social housing buildings, often in poor and vulnerable conditions. In order to address the solution regarding building renovations from the social, structural, and energy efficiency perspectives, in the framework of the Horizon Europe REHOUSE (Renovation packagEs for HOlistic improvement of EU's bUildingS Efficiency, maximizing RES generation and cost-effectiveness) Project, this paper proposes an integrated methodology of building assessment that was tested on a social housing building in Margherita di Savoia, a small town of Apulia Region, Italy. In addition to the structural and energy aspects, the social one is particularly important since the building is located in the "Capitanata Area", considered to be one of the most socially vulnerable areas in Italy. For this reason, an assessment methodology must consider reducing the overall impact of the assessment activities while explaining to tenants the purpose of the assessment and future renovation actions, maintaining the accuracy of the assessment results. Therefore, this study outlines an assessment methodology, demonstrated through its application to the case study building, that integrates the structural, energy, and social aspects, showing that the tenants' involvement is also crucial for the technical evaluations. The final result is a low-impact approach for the building knowledge gathering needed to start a deep renovation intervention in social housing.

Keywords: social housing; energy retrofit; structural assessment; weak social groups; reinforced concrete

1. Introduction

The continuous and evident impact of climate change makes the need to develop solutions to reduce greenhouse gas emissions urgent. The building industry is called to play a key role in this sense since it is responsible for about 35% of the total energy consumption and 38% of the greenhouse gas emissions globally [1]. As reported by Eurostat energy balances and the EEA Greenhouse Gas Inventory, 2023, 85% of EU buildings were built before 2000 and, amongst those, 75% demonstrate poor energy performance. In addition, around 40% of the energy consumed in the EU is used in buildings and over 1/3 of the EU's energy-related GHG emissions come from buildings. Acting on the energy efficiency of buildings is therefore key to saving energy, considering that about 80% of the energy used in EU homes is for heating, cooling, and hot water [2].

Moreover, the same buildings often lack adequate seismic protection, necessitating reliable assessment methods and sustainable intervention techniques that reduce time, costs, and disruptions [3]. The existing reinforced concrete (RC) structures often have inadequate detailing, poor behavior of the fragile elements, and substandard materials, as evidenced by recent seismic events [4]. In fact, the recent earthquakes have demonstrated significant losses due to insufficient seismic requirements [5]. Therefore, advanced methods for assessing and monitoring structural integrity have been developed to understand the building behavior and evaluate the retrofit strategies [6]. In particular, RILEM TC 249-ISC [7,8] has recently published the Recommendations on NDT in situ strength assessment of concrete, introducing a new methodology to reduce the errors in the technical assessment following the UNI EN 13791:2019 standard [9]. The RILEM methodology is easy to apply and can provide results (mean strength estimates and local strength estimates) that are equivalent to or more accurate than those provided by the previous approaches; mostly, this can save a significant amount of destructive testing (which is mandatory anyway) through the conditional coring option [10,11] without any additional cost. Furthermore, outdated envelope solutions and mechanical systems lead to high energy consumption, which is unsustainable both environmentally and economically.

Therefore, in recent years, there has been a shift towards combining or integrating structural and energy measures to minimize the intrusiveness of renovation actions while maximizing energy efficiency and living comfort as well as reducing seismic risk [12,13]. Several research projects at the Italian and European levels have focused on promoting such enhancements in building renovation projects. The integration of structural and energy efficiency aspects should also be considered in the assessment phase and not only when designing.

Even though the integration of energy and seismic interventions has been a novelty [6,14] in the last decade, pushing the construction industry towards improved sustainability [15], poor attention has been paid to the social aspects [16]. In fact, building renovations have significant social implications, especially for low-income groups. Affordability is a primary concern as renovations often lead to increased property values and rents, potentially pricing out long-term residents. This can result in relocations, either temporary or permanent, which is particularly challenging for those with limited financial resources. The disruption of established community networks and support systems can be especially impactful for low-income groups who rely heavily on local resources.

While renovations can greatly improve living conditions, there is a risk that those who need these improvements most may not benefit if they are forced to relocate due to increased costs or due to the time needed to perform the work and interventions inside the building. Energy-efficient renovations can help to reduce utility costs, which is particularly beneficial for households struggling with energy poverty. However, the initial cost of such renovations may be prohibitive without financial assistance.

The health impacts of renovations are another crucial aspect [17]. Addressing issues like mold, poor insulation, air quality, or outdated systems can significantly improve health outcomes for residents, which is especially important for low-income groups who may have been living in substandard conditions. However, low-income residents often lack the means to influence renovation decisions that affect their living spaces, highlighting the need for inclusive planning processes that involve caring about social aspects.

By considering these social aspects, renovation projects can be designed to benefit all the members of a community, including its most vulnerable residents, promoting social equity and sustainable urban development, enabling the residents to participate in the decisions regarding their buildings.

However, considering social aspects is also necessary at the assessment level. It consists mostly of preventing invasive tests to collect information on material properties and detailing of structural and non-structural members to achieve the required knowledge to perform the thermal and structural numerical simulations needed to assess the as-built conditions in order to reduce (or avoid) the temporary relocation and costs regarding completing the restoration of dwellings.

In this framework, this study, as part of the Horizon Europe REHOUSE (Renovation packagEs for HOlistic improvement of EU's bUildingS Efficiency, maximizing RES generation and cost-effectiveness) Project involving 25 partners from eight European countries, aims to apply and monitor some newly developed solutions (renovation packages, RPs) on four demonstration (demo) buildings located in Italy, France, Hungary, and Greece. During the assessment phase of the Italian demo building, the ENEA (the Italian National Agency for New Technologies, Energy and Sustainable Development) and UNIBAS (Department of Engineering, University of Basilicata, Potenza, Italy), which are REHOUSE Project [18] partners, through a multidisciplinary research team, developed a methodology that can serve as a guideline for an integrated social housing (structural, energy, and social) assessment devoted to upgrading interventions.

Therefore, this paper aims to describe the methodology and its application to the Italian demo building in order to demonstrate the procedure and its main advantages, as well as the benefits of such an integrated approach. After the description of the demo building, the methodology is shown from the structural, energy, and social points of view. Then, the results of its application to the building are finally discussed.

2. The Case Study Building

The Italian demo site building (IDSB), also named "Building A", is part of a residential complex of reinforced concrete social housing units designed in the early 1980s, located in the municipality of Margherita di Savoia, (province of BT, Apulia Region, Figure 1a), being in the "Capitanata" area, which is considered to be one of the most socially vulnerable areas in Italy [19].

(a) (b)

Figure 1. (**a**) Geographical location of Margherita di Savoia; (**b**) location of building A; (**c**) building view from the northwest corner.

The building (Figure 1c) is located in a sub-urban context between the salt mines on the southwest side and the sea on the northeast side (Figure 1b). The knowledge about the structural entity from a geometric standpoint, material properties, and reinforcement amount and layout is based on the information gathered from the design documentation made available by ARCA Capitanata, which is the building's owner.

It was possible to retrieve the architectonic design documents, structural design drawings, final testing, and approval of the structure. The building has a rectangular layout (22×11 m^2) and is built on four inhabited levels plus a terrace level. The foundations are composed of an RC plate stiffened by beams, while, on the accessible roof, there are compartments used as storage spaces. The load-bearing structure is composed of reinforced concrete with frames arranged in the two main plan directions of the structure and floor slabs of cementitious screed type. An elevator shaft is positioned on the long side of the building and adjacent to the staircase.

The structural design dates back to 1984, while the static tests at the building's structure completion were conducted in 1986. The design accounted for seismic actions according to the classification of the Margherita di Savoia municipality dating back to 1981.

The frames show a prevalence of wide beams (depth lower than width). Floor slabs are composed of reinforced concrete T-shaped joists with hollow clay lightening bricks. Their total thickness is 24 cm, including 20 cm for the joists and 4 cm for top plate, which is reinforced with a steel net. Therefore, floor diaphragms can be considered to be rigid for in-plane actions (Figure 2).

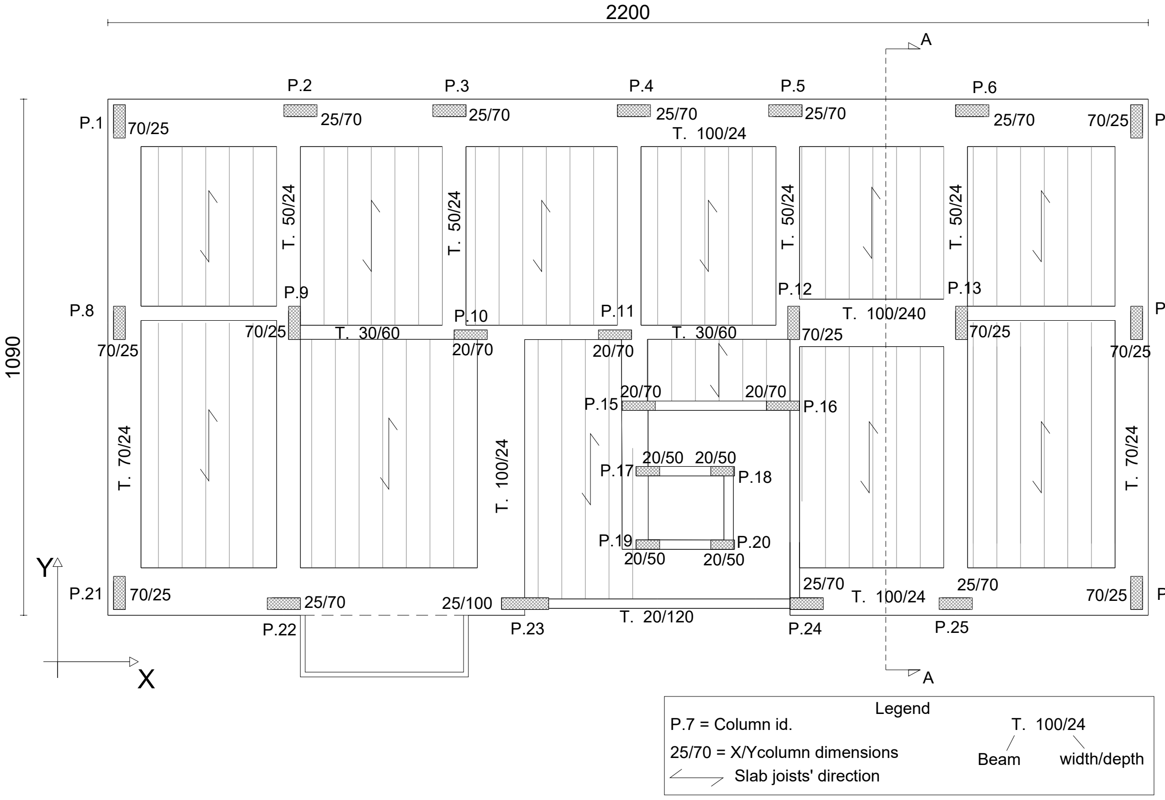


Figure 2. Typical structural plan.

The structure has globally 5 stories (4 ordinary + roof story) with a floor area equal to 220 m^2 and an interstory height of 3 m (Figure 3).

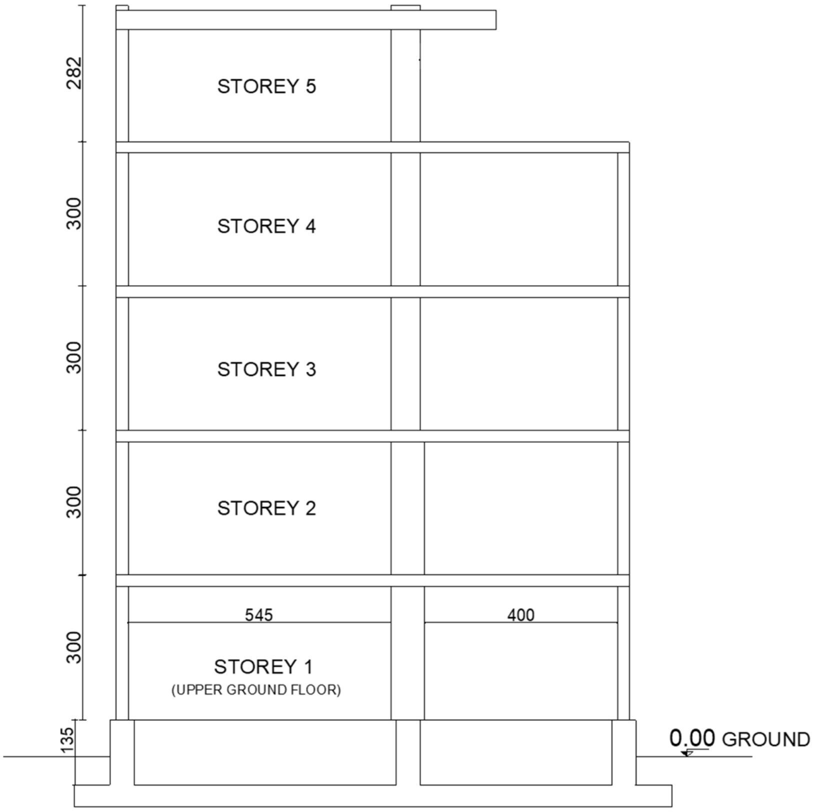


Figure 3. Structural section A–A (dimensions in cm).

The frame and slab structure are composed of R'bk 250-grade concrete with a cubic characteristic compression strength of 25 MPa and FeB 44K-type reinforcing steel, which has a characteristic yielding stress equal to 430 MPa. Typical dimensions of columns are 70/25 cm, while the beams' dimensions (width/depth) are 100/24 cm (for the border ones), 70/24 cm, and 50/24 cm (Figure 2). Only a few beams connecting columns 8 to 11 have a depth higher than the width, being 30/60 cm, as can be seen from Figure 2. No information about any structural intervention during the building's life was found in the collected documents.

The envelope walls are composed of a single layer of perforated clay blocks with a total thickness of 37 cm with additional plaster layers inside and outside that are 15 mm thick. These blocks are placed externally with respect to the column frame elements, in line with the beam edges, the latter in order to minimize the thermal bridges in correspondence to columns, which are covered by 8 cm thick hollow clay brick layers. In the lower part of the building, in addition to the mentioned infill system, there are cladding elements like perforated 80 mm thick bricks and 20 mm thick marble layer, serving an aesthetic function. From the systems point of view, the apartments are equipped with independent heating systems. The boilers are powered by natural gas (methane). Three apartments have heat pumps for winter and summer air conditioning. More details about the building systems are available in the detailed energy audit section.

3. Methodology: The Integrated Structural–Energy–Social Assessment Approach

The integrated assessment methodology includes 10 steps that gradually enable the practitioners to gather information regarding the building, considering the tenants' experience in using it and their knowledge of possible interventions and accidents not reported in the design and maintenance interventions documents. Moreover, involvement of tenants is crucial to make more informed decisions that can become more acceptable by themselves.

Therefore, while a traditional structural assessment foresees steps 2, 3, 6, 7, 8, and 9 (Table 1), in the proposed methodology, step 2 is preceded by step 1, devoted to gathering information directly from tenants about any intervention or accidents not reported in the official documentation. Step 1 also serves to explain to tenants the assessment activities, making them more bearable. Furthermore, steps 4 and 5 precede and help to carry out step 6 in which destructive and non-destructive investigations are planned. Step 4, in fact, beyond the traditional preliminary surveys, includes some instrumental diagnostics to evaluate the matching of the as-built condition and design drawings. This enables making a preliminary evaluation of structural criticalities at step 5. The latter clearly underscores whether or not the building could present significant structural and/or seismic protection gaps, necessitating a detailed structural assessment.

Table 1. Methodology steps.

Step	Description	Social	Structural	Energy
1	Questionnaire delivery and collection of existing documentation (from owners) in synergy with questionnaire (from tenants)	√	√	√
2	Historical critical analysis of the building		√	√
3	Definition of the knowledge level to be achieved		√	
4	Preliminary inspections: geometric and structural survey also using diagnostic techniques (thermographic, pacometric, GPR measurements, and laser scanner)		√	√
5	Rapid assessment of structural criticalities using the ENEA App "Condomini+ 4.0"		√	
6	Definition of destructive and non-destructive investigation program	√	√	√
7	Non-destructive investigations (ultrasonic and sonic measurements)		√	
8	Performing destructive investigations (e.g., columns' coring)		√	√
9	Detailed structural analysis and seismic vulnerability assessment		√	
10	Detailed energy audit	√		√

Regarding the energy efficiency evaluation, it usually requires steps 2, 4, and 10. In this methodology, step 1 is helpful in identifying the tenants' habits and real energy consumption values (thorough the electricity and natural gas bill collection). Moreover, the envelope properties are better recognized thanks to the structural and non-structural tests (steps 6 and 8), which enable the reconstruction of stratigraphy for the several types of infills (e.g., in presence of cladding in different parts of the façades).

Moreover, for every step specifically devoted to structural or energy aspects, the tenants' needs and expectations (if any) are considered and evidenced in the related column of Table 1.

4. Results of the Methodology Application to the Case Study Building

4.1. Social Aspects and Questionnaire Delivery

The first step in approaching a building for renovation is to obtain general information to assess the existing conditions, facilities, and infrastructure. In addition, it is important to obtain information about the building's inhabitants, their consumption patterns, and needs.

In the REHOUSE Project, to obtain this information, two questionnaires were proposed: one to be submitted to the tenants of the social housing and one to be submitted to the building owner.

The first one aims to capture and discover both end users' needs and expectations, defining what building features are essential for these users. The questionnaire was based on a "participatory design approach" that combines the expertise of the system designers with the perceptions and needs of people who are affected by the energy renovation changes. The set of questions were prepared together with representatives of two key actors: ARCA Capitanata, the territorial housing agency, and Apulia Region (both public entities), playing a double role as a facilitator (thanks to the experience and skills of the person in charge of the activities) and co-financing the energy renovation of the building. The question was divided into four sessions: demography, energy behavior, building requirements, life quality and neighborhood, and final considerations. The results of the questionnaire have been used to match the items of the interviews with the technical and energy behavioral information useful for the energy audit.

The questionnaire was proposed in the form of a face-to-face interview with the mediation of the "social facilitator" (Apulia Region) to simplify the questions and gather as much information as was useful for the purposes of the energy audit. The tenants were interviewed regarding the technical site visit related to the energy audit and the structural analysis. It was an opportunity to explain what the technicians were working on.

The answers were used in the design phase and discussed in order to evaluate how the renovation process could impact the life of the end user.

In such a way, in the REHOUSE Project, the role of the designers thus became less about 'designing for' and more about 'designing with' the users and other stakeholders [20]. It became the end users' engagement phase, where the face-to-face meetings had the purpose to hand out knowledge pills to the users on "Energy Efficiency First" topics [21].

The second questionnaire was addressed to the owners of the building in order to collect all the information on the building: general psychographic questions, current energy performance, structural analysis of the building, renewable energy sources, and other information available (plans, BIM, etc.).

4.2. Historical Critical Analysis

This phase consists of collecting all the documents related to the building construction and subsequent maintenance interventions. As mentioned, a series of design documents were provided by the building owner, which enabled understanding the structural arrangement and materials used for the construction (as already shown in Section 2). Moreover, a series of interviews with the tenants were important in terms of gaining insight regarding any maintenance interventions not mentioned in the documents and about any accidents that occurred. As an example, some tenants reported the occurrence of a fire on the second floor a few years before, which suggested performing a load test on the related portion of slab in order to verify its condition. Furthermore, other tenants reported some water seepage across the roof slab, which suggested carrying out more accurate infrared camera investigations. The information gathered through the tenants' help provided very useful knowledge in terms of determining the current condition of the building and its damaged and degraded elements.

4.3. Definition of the Knowledge Level

The knowledge level (KL) represents the accuracy of the information related to the building for the structural assessment, and this affects the confidence factor (CF) that should be used to reduce the material strength values. There are three possible knowledge levels according to the Italian building code:

- KL1, the lowest knowledge level corresponding to CF = 1.35;
- KL2, the intermediate knowledge level corresponding to CF = 1.2;
- KL3, the maximum knowledge level corresponding to CF = 1.0.

Even though it could be desirable to obtain KL3, that knowledge level is more expensive since it requires a large number of investigations and is also invasive due to the concrete cover demolitions that have to be completed to perform all the needed surveys. In order to balance the need for detailed knowledge and that related to reducing the invasiveness of the structural investigations, in agreement with the building owner (ARCA Capitanata), the selected knowledge level was the intermediate one, i.e., KL2, with a confidence factor CF = 1.2. This choice directly affects the extent and number of structural tests to be carried out.

4.4. Preliminary Inspections

A step of the integrated methodology is to plan the preliminary investigations for the geometric and structural survey to reach the set knowledge level.

The characterization of materials and structural elements represents a problem in the case of inhabited buildings, in which it is not possible or difficult to carry out destructive tests but also non-destructive tests due to some difficulty in accessing the elements to be tested and also due to the impossibility to remove plaster or coverings. Therefore, a procedure has been developed that meets these needs.

A procedure is described below that aims to significantly reduce the in situ destructive tests in inhabited buildings and to limit as much as possible the invasiveness of the tests carried out, including non-destructive ones, as well as reducing the number of visits to disturb the tenants as little as possible.

Figure 4 summarizes the operations necessary for the preliminary knowledge of the building in order to plan the test campaign on the structural and non-structural elements for more detailed knowledge. The three blocks in the diagram are non-consequential operations, for which the procedures can also be carried out at the same time.

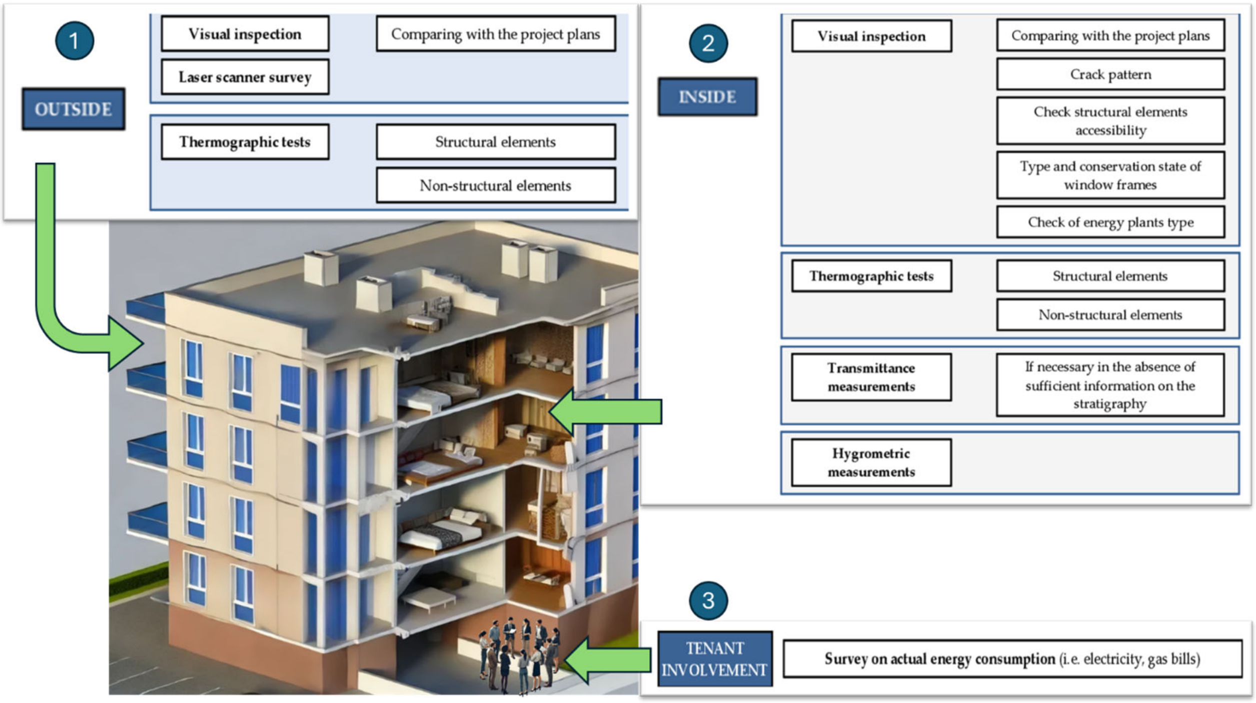


Figure 4. Example overview of preliminary surveys and inspections on the building.

The first block (1) concerns the external survey, which involves visual inspection and surveying with laser scanners and other diagnostic techniques (thermographic, hygrometric, pacometric, and GPR measurements) to be compared with the design drawings. The thermographic inspection, in particular, makes it possible to identify any discontinuities or deterioration, structural or non-structural, of the building envelope, in particular on columns, beams, and floors; it also makes it possible to identify thermal bridges, infiltrations, and surface cracks on walls and other surfaces.

The second block (2) involves the survey operations carried out inside. Among these, in order to obtain further information, it is important to be able to carry out, in addition to thermographic measurements, hygrometric measurements since they enable (without affecting the concrete) verifying the presence and/or distribution of moisture up to a depth of 30 cm and to determine whether it is a temporary or persistent phenomenon on the masonry materials and packages also affected by hygroscopic moisture phenomena.

The last block (3) of the diagram refers to the social analysis. As mentioned before, the integrated methodology includes the involvement of the tenants in the assessment investigation. It is a participatory assessment approach, where the expertise of the system professionals is combined with the needs of the tenants affected by the renovation changes. Professionals, thanks to the support of the social facilitator, meet tenants and inform them regarding the whole assessment process. This step includes obtaining information relating to energy consumption (e.g., electricity and gas bills).

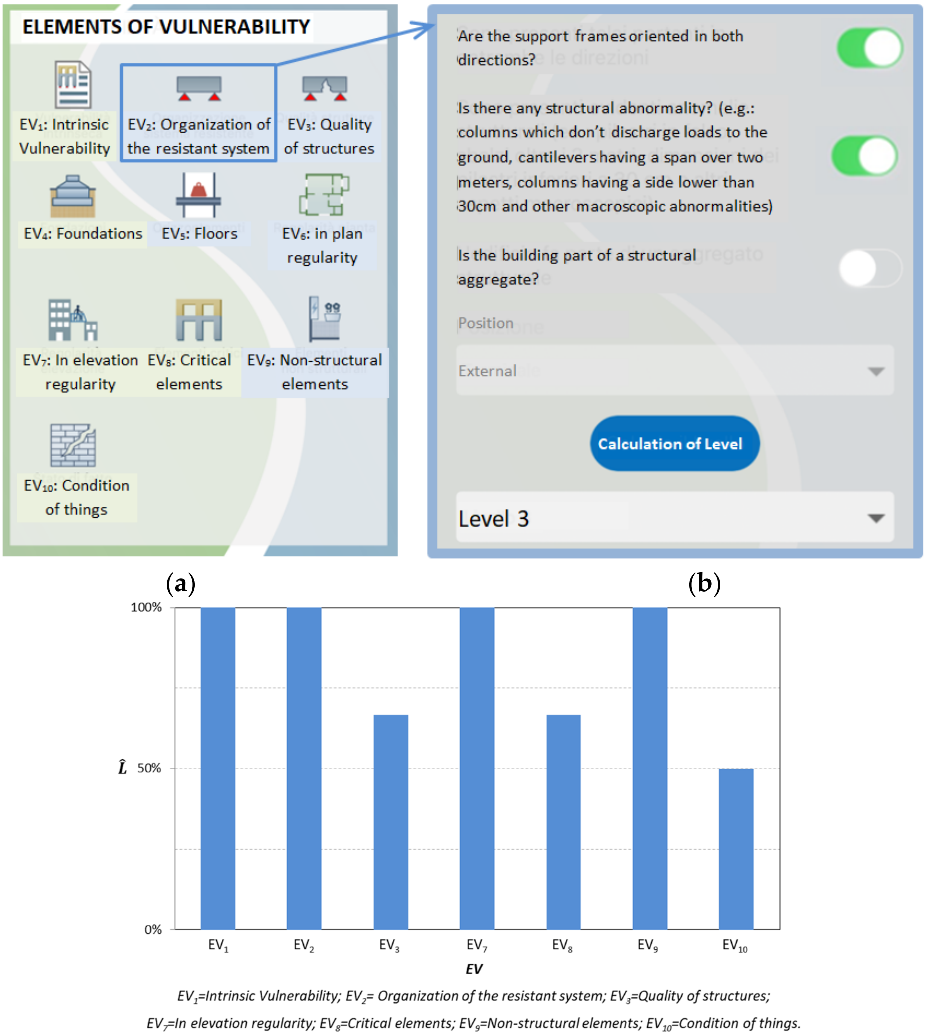
In summary, the preliminary inspections played an important role in the rapid assessment of the construction problem, type, position, and size of the vertical and horizontal structural elements, moisture problems, damage and crack localization, and energy plant type. They played a significant role in identifying the structural elements to be tested, especially with regard to their accessibility.

4.5. Rapid Structural Assessment Through the ENEA App "Condomini+ 4.0"

A preliminary structural assessment of the building was performed through the ENEA app "Condomini+ 4.0" [22]. This evaluation, which can be defined as expeditious and qualitative, is not based on instrumental tests and numerical simulations and therefore does not return a vulnerability analysis. However, resting on well-known structural deficiencies and seismic effects, it enables revealing the structural criticalities inferable from a thorough study of the technical documentation and a visual inspection of the building. A wizard guides the specialist through the investigation of the most representative elements of vulnerability (EV_{is}), listed in Figure 5a, up to obtaining an estimation of the level of intervention (L_i) expected for each of them. Each L_i can take a value between 1 and L_{i_max}, and it increases with the relevant issues. If $\hat{L}_i = L_i / L_{i\_max} = 100\%$, it means that L_i reached its threshold value and the corresponding EV_i is highly critical. For the case study, the calculation of the level of intervention concerning the organization of the resistant system is reported, by way of example, in Figure 5b, and all the EV_{is} with $\hat{L}_i \geq 50\%$ are synthetically represented in Figure 5c. The corresponding criticalities are briefly described below.

- EV_1 The documentation the design report is lacking, and, therefore, important technical information is missing.
- EV_2 Some columns have a side lower than 30 cm, which is likely to have negative repercussions in terms of resistance and deformability.
- EV_3 In some areas, steel reinforcements are not adequately coated.
- EV_7 There is a significant percentage change in the area between the last story and the lower ones. Moreover, the effects of the presence and arrangement of knee beams between stories should be numerically explored.
- EV_8 Columns of stairs are stocky elements that could be prone to shear failure. The activation of fragile mechanisms is likely.
- EV_9 Non-structural elements require particular attention in terms of connections to the structural parts and in terms of stability over seismic actions.
- EV_{10} Portions of plaster detached from the facades and some expulsions of concrete covering have been noted. Interventions aimed at removing falling parts and refurbishing damaged and/or deteriorated zones are required.

Finally, by weighing all the L_{is}, the app provides an overall level of intervention (L). This parameter is a synthetic index of the structural deficiencies revealed by the investigation and increases on a scale from 1 to 6. For the case study, a value L = 4 was obtained, which means that, overall, the building has a medium–high criticality level, which suggests performing a detailed structural/seismic assessment, as reported in the following.



Are the support frames oriented in both directions?

Is there any structural abnormality? (e.g.: columns which don't discharge loads to the ground, cantilevers having a span over two meters, columns having a side lower than 30cm and other macroscopic abnormalities)

Is the building part of a structural aggregate?

Position: External

Level 3

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

EV_1=Intrinsic Vulnerability; EV_2= Organization of the resistant system; EV_3=Quality of structures; EV_7=In elevation regularity; EV_8=Critical elements; EV_9=Non-structural elements; EV_{10}=Condition of things.

(**c**)

Figure 5. (**a**) List of EV_i investigated through the app; (**b**) example of calculation of the level of intervention concerning the organization of the resistant system; (**c**) synthetic representation of EV_i with $\hat{L}_i \geq 50\%$ (extracted from ENEA app "Condomini+ 4.0).

4.6. Definition of Destructive and Non-Destructive Investigation Program

4.6.1. Destructive Tests

It is worth noting that the preliminary rapid assessment conducted using the "CONDOMINI+ 4.0" app, shown before, enabled highlighting some criticalities that indicate a possible poor seismic performance of the building at hand. In particular, the above-mentioned assessment evidenced, among other issues, the existence of short and stiff elements in the staircase, which could fail through fragile mechanisms or the presence of elevation irregularities (roof level) due to floor plan surface variations. Therefore, an immediate detailed assessment is necessary to carefully evaluate the structural and seismic vulnerability of the building. Thus, it is first necessary to plan destructive investigations that are able to provide the needed information about the material properties, structural details, and geometry, which can enable performing a detailed assessment according to the rules of the Italian building code [23,24].

As already mentioned, the design of structural investigations is crucial both to confirm the hypotheses formulated during the preliminary phases and to obtain a realistic estimate of the physical and mechanical parameters to be used in the structural verifications. In the case at hand, considering that the building is fully occupied, the survey program to achieve knowledge level KL2 was designed to minimize the invasiveness of the tests and be socially acceptable. Except for the concrete cores, the survey locations were chosen following a careful analysis of the information gathered, the preliminary study of the building, and the site inspection carried out inside each apartment. Concerning the concrete cores, the investigation points were chosen using the valuable information provided by the sonic measurements carried out by the ENEA, mentioned in Section 4.7.

According to the code definition of "limited tests", 15% of the structural members must verified and 1 concrete + 1 steel rebar sample should be extracted from each building story. This means that the following total investigations must be conducted:

- Thirty-seven GPR scans and endoscopy test to check the number of rebars inside columns and beams;
- Two visual inspections to check reinforcement layouts (by concrete cover removal);
- One visual inspection on infill walls;
- Two endoscopy inspections to check the foundation typology;
- Extraction of eight cores from column members to assess the concrete compressive strength. It was not possible to extract cores from beams since they have the same thickness as the slab and therefore are not suitable for this purpose;
- Extraction of six steel rebars from columns and roof story beam members.

It is worth noting that all the most invasive investigations like concrete coring and steel rebar extraction were performed from the building's outside using an aerial work platform in the staircase or at the roof level. This enabled preventing any damage to the finishing of the dwellings and the related disruption for the tenants.

4.6.2. Non-Destructive Tests

The assessment of the compressive strength of structural concrete can be conducted by (i) destructive coring tests in varying amounts (Section 4.6.1) and (ii) calibrated indirect methods, combining destructive coring with non- or semi-destructive techniques. The use of coring is a time- and labor-intensive method that weakens the existing concrete structure, leaving a lasting impression on it. Alternatively, several non- and semi-destructive techniques are available for in situ determination of compressive strength that must be appropriately correlated with destructive testing. Moreover, in order to minimize disruptions to the tenants/owners, wide use of non-destructive testing (NDT) techniques occurs following the Recommendations on NDT in situ strength assessment [25]. Below is a summary of the operations to be performed to act in accordance with the RILEM Recommendations [7] adapted for a regular building, such as the IDSB, in which the inhabitants live in the apartments and all the apartments are plastered. The NDT testing phases are as follows:

1. Definition of the number of tests on materials and structural elements for their characterization, according to the current European and Italian/local technical standard in order to achieve a knowledge level as defined in Section 4.6.1.
2. In compliance with the RILEM TC 249-ISC Recommendations [7], definition of the prescribed minimum number of cores on the basis of prior knowledge about the range of concrete properties (Section 4.6.1).
3. Execution of a wide campaign of ND tests on the columns of the building in order to evaluate the effectiveness and feasibility of implementing the RILEM TC 249-ISC [7] methodology to reduce the error in the technical assessment following standard UNI EN 13791:2019 [9]. The information from this extensive test campaign, conducted on the results of the data collection obtained in the preliminary inspection (Section 4.4), is necessary to define the columns on which to carry out the measurements. At the beginning of the test campaign, it is important to identify the position of the column-reinforcing bars using a pacometer and/or a georadar (GPR scanner). After these mandatory inspections, it is possible to carry out a campaign of ultrasonic measurements on the inspected columns using the direct method, for columns accessible from opposite sides, and/or the indirect method, for columns accessible from one side only.

4. Data analysis starting from the results of the ND test campaign in order to identify the columns from which to extract the cores on which to perform compression and ultrasonic tests for the characterization of the concrete. The same data analysis process enables evaluating the reduction in the number of cores.

4.7. Non-Destructive Investigations (Sonic Measurements)

Indirect sonic measurements were performed on the IDSB's columns to help in selecting the columns from which to extract the cores. The sonic velocity test technique is based on the generation of mechanical impulses with frequencies in the sound field. The sound wave is generated on the element, the column in the specific case of this measurement campaign, by impacting with an instrumented hammer (green object in Figure 6a) and is received by a sensor (piezoelectric accelerator) placed at a different point on the element (red object in Figure 6a). To calculate the sonic velocity, it is necessary to measure the travel time of a sonic signal through a surface. In our case, indirect measurements were carried out, placing the impact point of the instrumented hammer and the receiving accelerator on the same face of the column as reported in Figure 6a. It was necessary to conduct indirect measurements due to the difficulty in taking direct ultrasonic measurements because the opposite sides of the pillar were not accessible. The measurements were carried out by Level 3 personnel (Figure 6b) trained according to [26].


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

Figure 6. Indirect ND measurements on a column: (**a**) testing scheme and (**b**) execution.

The execution of the tests on the columns required careful planning and time to agree on the co-presence of the tenants, without whom it would not have been possible to access the apartments. Previous inspections (Section 4.4) made it possible to optimize the intervention times by not considering the columns that did not have a clear surface; in many situations, it would have been impossible, or extremely complicated, to move the furnishing elements.

It is worth remembering that, for the correct execution of sonic tests, it is necessary to have both a free column surface and also a sufficiently large space in front of it so that the instrumented hammer can facilitate the correct excursion to impact the column with energy suitable for the propagation of the sonic impulse.

Taking these limitations into account, it was still possible to conduct a large series of indirect sonic measurements, which were performed by positioning the point of impact of the instrumented hammer on the column at a height of 2 m from the floor and, with alignment on the vertical, the accelerometer at a distance of 15 cm from the floor (Figure 6a).

Table 2 shows the velocities calculated on the flight time measurements, sorting the data first based on the ascending column identifier, then by ascending story.

Table 2. Indirect sonic velocity measurements to support structural analysis on the IDSB.

		Indirect Sonic Velocity [m/s]				**Indirect Sonic Velocity [m/s]**	
Column ID	**Story**	**Mean Value**	**Std. Dev.**	**Column ID**	**Story**	**Mean Value**	**Std. Dev.**
1	1	3696.8	79.1	21	1	3939.7	116.3
1	2	3080.5	84.6	21	2	3095.4	12.9
1	3	3690.5	34.3	21	4	3403.1	28.0
2	1	3064.9	31.1	23	2	3601.8	28.4
3	4	3550.9	5.6	23	4	3762.8	22.0
6	3	2889.4	72.6	24	2	4186.2	53.7
7	1	3810.2	119.3	24	3	2896.5	62.0
7	2	3679.6	123.5	25	3	3425.9	9.0
7	3	3085.5	37.8	25	4	4103.2	71.1
15	1	3895.2	41.0	26	1	4171.8	145.5
15	2	3967.3	28.1	26	2	3769.7	83.4
15	3	3629.9	133.5	26	3	3522.0	40.6
15	4	3157.6	42.1				

The mean values of the indirect sonic velocity measurements, summarized in Table 2, refer to the columns identified for the possible core samples in Section 4.6.1.

The distribution of the measurements is shown in Figure 7, and the average values of the sonic velocity measurements have a normal distribution for values between 3350 m/s and 4100 m/s, whereas there are concentrations for both low sonic speed values and high values.

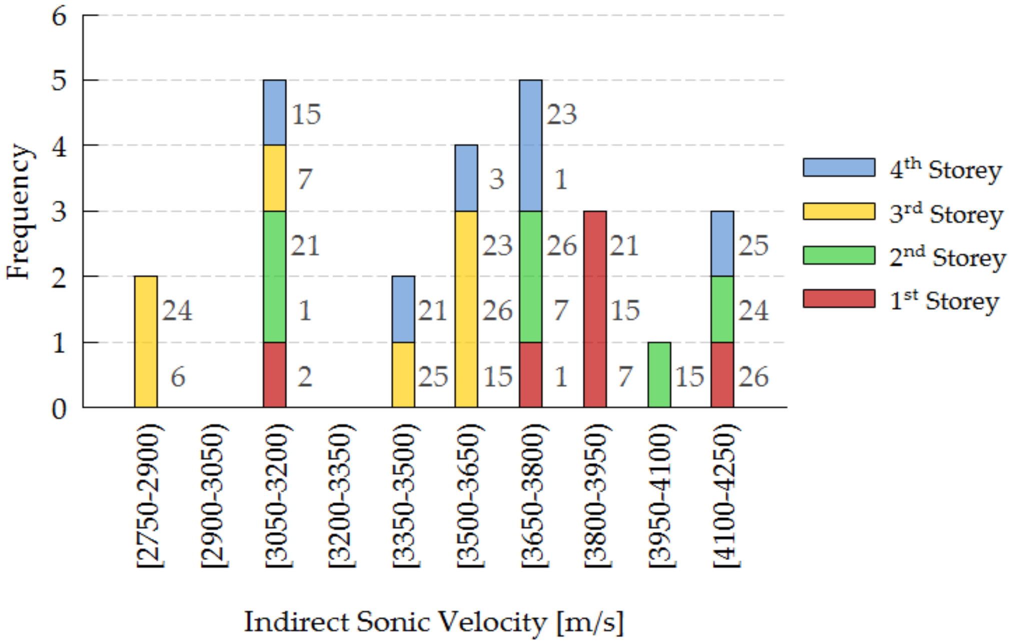


Figure 7. Distribution of indirect sonic measurements.

As mentioned in Section 4.6.1, eight samples of cores had to be extracted according to the regulations and guidelines for a KL2 level of knowledge (High Council of Public Works, 2019). Considering the situation of the IDSB, it was planned to extract no more than two cores per story (on different columns) and no more than two cores per column alignment (on different stories).

Keeping these indications in mind, it was suggested to follow the approach indicated by RILEM TC 249-ISC [7] using the information collected in the performed indirect ND measurement campaign; that is, to choose the positions from which to extract the cores so that the corresponding values of the sonic velocity measurements previously detected are distributed over the entire range.

To provide a more effective graphic representation, the entire series of sonic velocity measurements, sorted by increasing value, is shown in Figure 8 on the left, and the seven positions where core drilling was proposed are highlighted by black triangles. The right chart of Figure 8 shows the actual dispersion of the indirect sonic velocity measurements corresponding to the proposed coring positions (proposed positions in Figure 8).

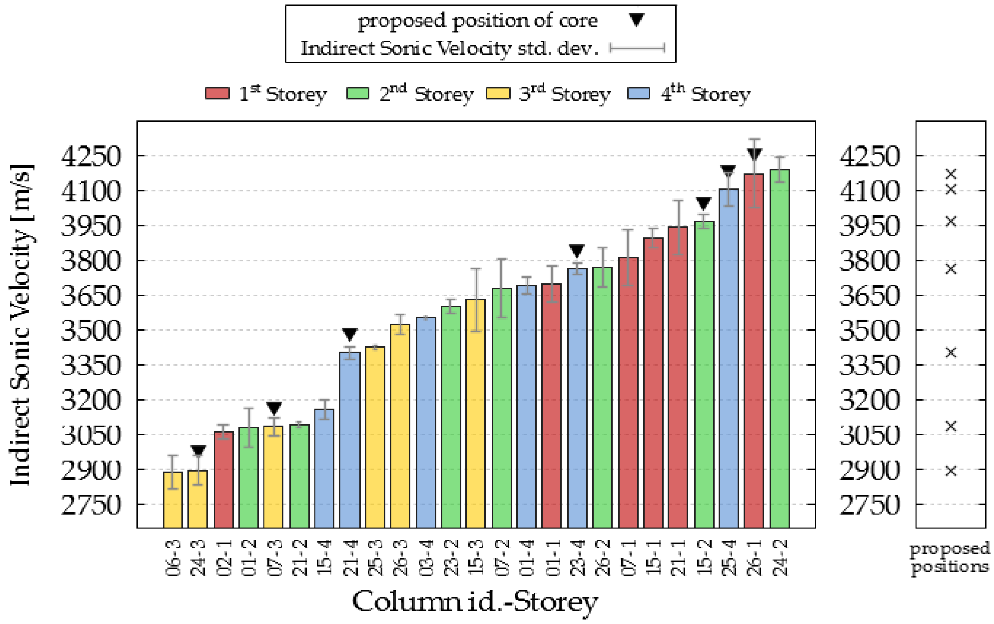


Figure 8. Sonic measurements and proposed positions for core extraction (velocity values sorted by ascending order).

4.8. Performing Destructive Investigations

4.8.1. Visual Inspections

The visual inspections (Figure 9) of the reinforcement details (type, diameter, and number of bars actually present) were conducted by means of seven exploratory tests distributed across various stories between the beams and columns, utilizing the extraction points of the reinforcement samples. In fact, the extraction of rebars requires concrete cover removal, and this represents an opportunity to also visualize the reinforcement layout, preventing additional visual inspections. Regarding the external column elements, given the typological homogeneity, it was sufficient to carry out only one test at the first story. The exploratory test on the infills and cladding elements occurred through a hole, combined with endoscopic investigation, to recognize the stratigraphy and transverse thickness of the infill panels. As the foundation level was not accessible, two additional endoscopic investigations were carried out through the foundation beams around the perimeter of the building to check their typology.

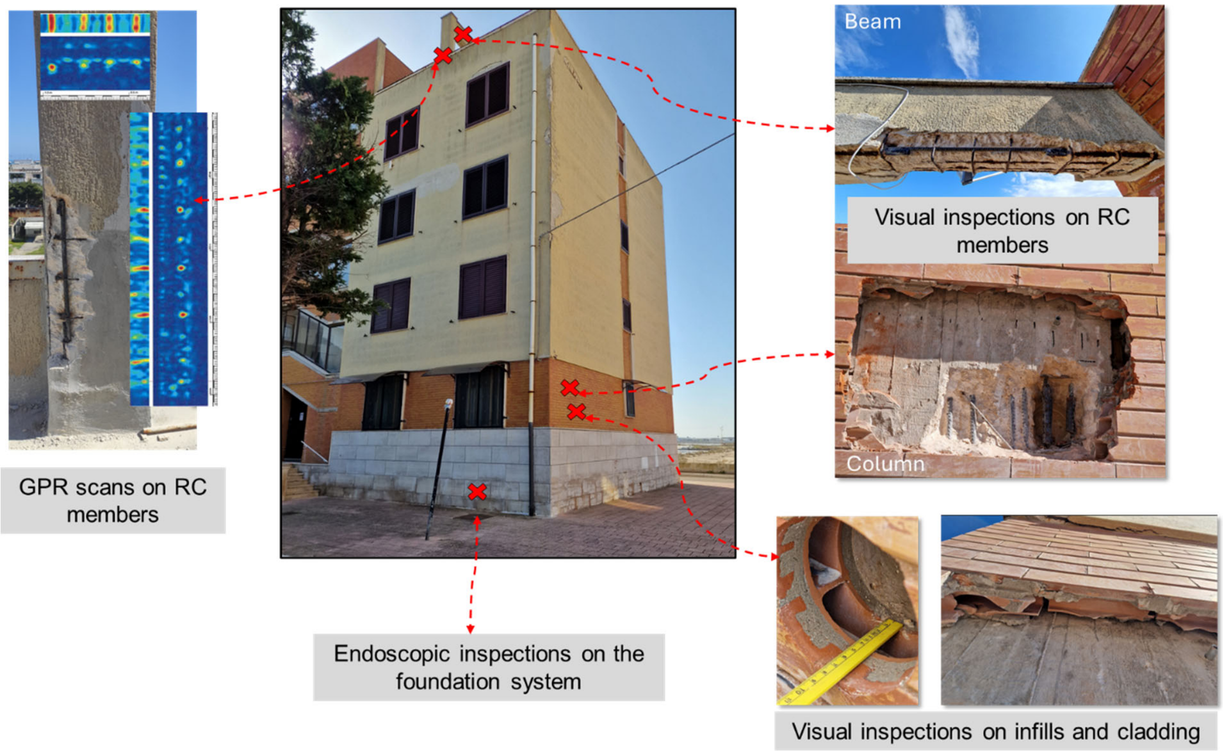


Figure 9. Overview of destructive investigations.

4.8.2. Coring Tests

The building has a floor area of approximately 220 m^2. To achieve the knowledge level KL2, a total of eight cores were extracted (two per story). Considering the difficulty of extracting samples from wide beams, the coring activities focused only on the columns. Each core has a diameter of 10 cm and a length of approximately 13 cm (Figure 10). The extraction procedure followed the standards of UNI EN 13791:2019 [9].

Core	Storey
C1	5
C2	1
C3	2
C4	2
C5	3
C6	3
C7	4
C8	4

Figure 10. Concrete core drilling (for column and storey numbers, see Figures 2 and 3 respectively).

During this phase, the cladding of the external columns was recorded. At ground level, the cladding consists of Apricena stone slabs, terracotta strips, and a layer of plaster, with a total thickness of 6.5 cm. Near the columns, there is a cladding with a thickness of

13.5 cm, defined by a layer of plaster, perforated bricks, and an air gap. For this reason, this investigation phase is also related to the energy aspects since it provides information on the building's envelope.

The extracted specimens underwent compression testing according to the provisions outlined in standard UNI EN 12504-1:2021 [27]. The strength of the cores taken was converted to the corresponding in situ concrete strength before being utilized in verification calculations according to a widely used procedure Masi (2005) [28].

4.8.3. Extraction of Rebars

Given the steel design specifications and considering the operational difficulties in extracting reinforcement samples from the beams, the extraction of the six steel bars only involved the columns at specified levels (the fifth one) and by following the best practices devoted to avoiding any reduction in the load-bearing capacity of the column elements. During these activities, it was possible to verify the state of the rebars. Some column and beam rebars were corroded, and the cover was spalled, indicating some effect (e.g., likely chloride penetration) of the salty environment due to the presence of the salt mines and the sea. However, this problem was related only to the RC members of the roof story, which were not protected by the infills. Therefore, corrosion effects were not considered in the following assessment phase.

The reinforcement-extracted specimens, with a length of approximately 60 cm (Figure 11), underwent tensile failure testing in accordance with standard UNI EN ISO 6892-1:2020 [29].

Figure 11. A column rebar before the extraction.

As a result of the structural investigations, the following material properties have been assumed in the subsequent calculations, and it was possible to finalize the finite element model to conduct the structural and seismic assessment:

- Mean concrete compressive strength fcm = 26.8 MPa;
- Mean steel tensile strength fym = 430 Mpa.

4.9. Detailed Structural and Seismic Assessment

The structural assessment and seismic evaluation occur via finite element analysis using a commercial software package [30] according to the Italian building code [23]:

The assessment procedure foresees the following steps:

- Structural analysis under static loads (service conditions), devoted to assessing the capacity of structural members under gravity loads.

- Damage limitation (DL) limit state seismic assessment, performed under frequent earthquakes devoted to verifying that interstory drift values do not exceed a threshold value (0.5% of the interstory height).
- Life safety (LS) limit state assessment: it provides safety checks of structural members under a less frequent earthquake in order to protect the structure with respect to possible life loss.

The static loads are those in Table 3.

Table 3. Gravity loads adopted in the assessment.

Load Description	**Load Value**
Reinforced concrete self-weight γ	25 kN/m^3
Residential floor slab variable load Qf	2 kN/m^2
Balcony and stair variable load Qb	4 kN/m^2
Infill wall self-weight γ	8 kN/m^3

The selected seismic analysis method is dynamic linear (modal). Therefore, the seismic action is modeled by design spectra. This choice accords with the observation that substandard buildings suffer fragile collapse related to shear actions in beam–column joints, beams, and columns. The latter often limits the advantages of using more advanced nonlinear analysis methods (e.g., pushover). Furthermore, looking at a large-scale application of this methodology, it must be considered that most practitioners conducting structural analyses use commercial software and linear analysis methods. All the data related to the seismic action definition are reported in Table 4.

Table 4. Seismic action model data.

Seismic Action Parameter	**Value**
Building Coordinates	LAT (ED50): 41.3797493 [°] LON (ED50): 16.1428204 [°]
Intended use	Residential
Use class	2 (ordinary buildings)
Use coefficient Cu	1
Nominal life duration Vn	50 years
Reference period Vr = Cu·Vn	50 years
Soil type	C
Topographic coefficient	T1 (flat)
Life safety (LS) return period Tr	475 years
Damage limitation (SLD) return period Tr	50 years
Life safety (LS) seismic design acceleration ag	0.195 g
Damage limitation (SLD) seismic design acceleration ag	0.076 g

4.9.1. Analysis Result Under Gravity Loads

Figure 12 shows the results of the gravity load verifications under the flexure and shear of the column and beam members. The colormaps report the demand/capacity ratio of the structural members, which is always lower than 1.0, meaning that no members reach the full-strength exploitation under gravity loads. This indicates that the gravity load verification is fully satisfied. Therefore, the capacity/demand ratio (safety factor) is higher than 1.0 (C/D = 1.03 for flexure and 1.11 for shear).

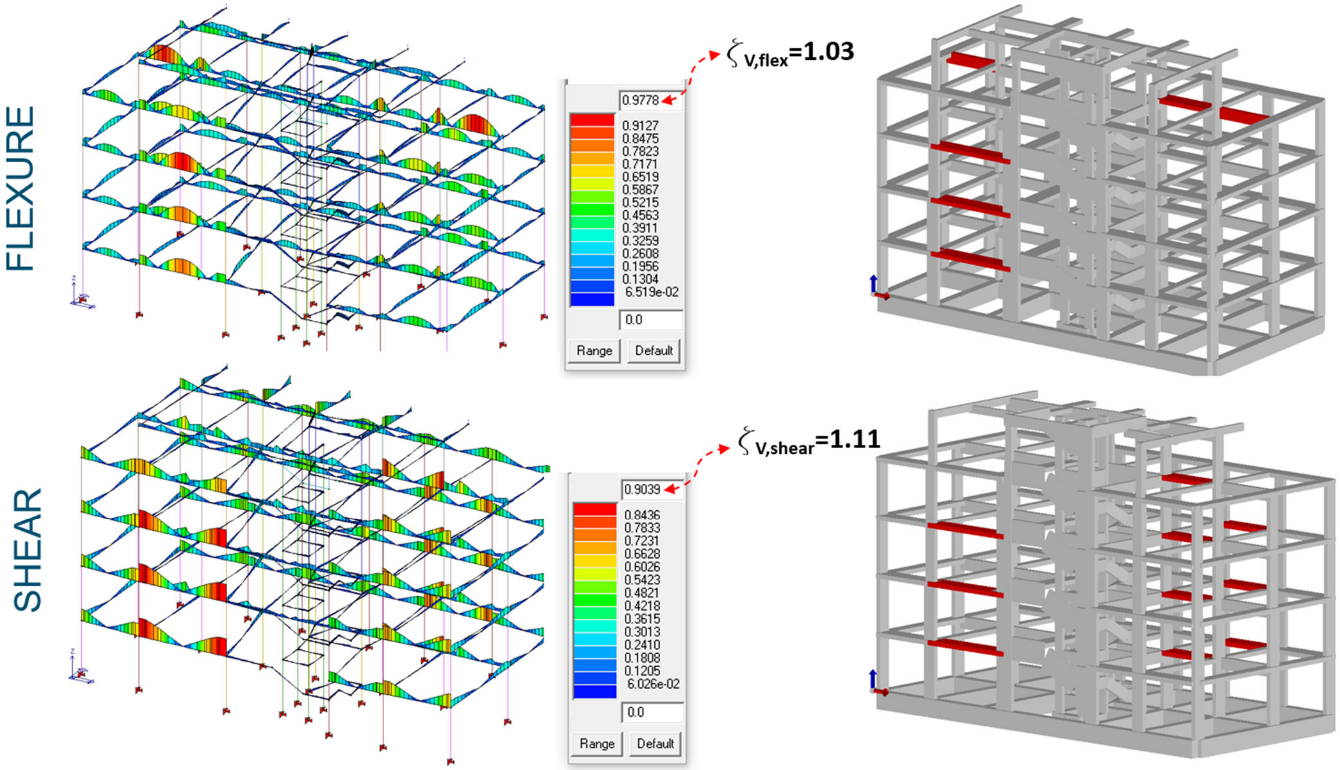


Figure 12. Gravity load verification (extracted from Pro_SAP software Startup version).

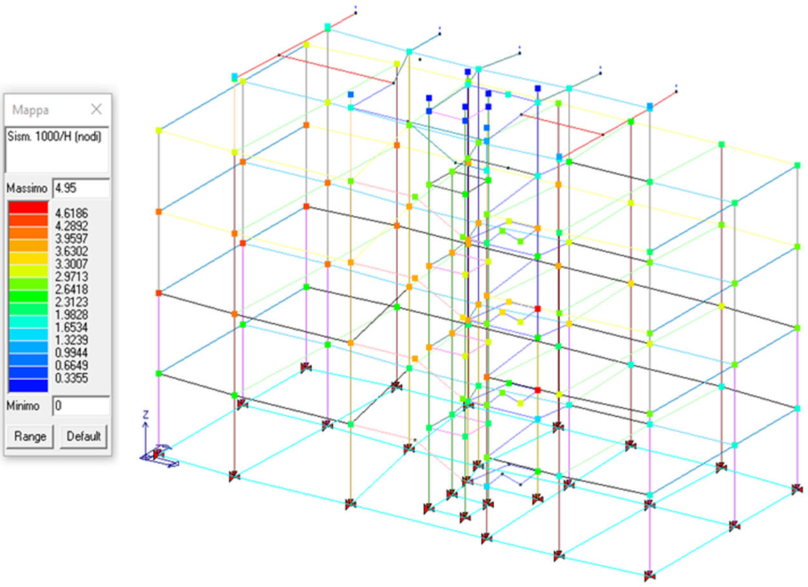
The red elements reported in Figure 12 on the right are those that first reach the limit condition represented by the achievement of the stress equal to the strength at the section level.

It must be noted that a careful evaluation under gravity loads is very important to prevent the execution of heavy and invasive interventions on RC members that almost certainly would require work inside the building, with related disruption. This step's result can represent a green light for low-invasive seismic strengthening interventions.

4.9.2. Seismic Analysis Results at Damage Limitation Limit State (SLD)

The damage limitation verification is only based on checking that the maximum interstory displacement does not exceed a predefined threshold aimed at protecting the integrity of non-structural elements like infill walls and systems in the as-built condition and, more importantly, in the post-intervention condition. In fact, the realization of renovation packages foresees the installation of new heat pump systems and related piping (connecting different floors) and a multipurpose façade composed of photovoltaic panels and insulation panels. The integrity of the latter is strictly related to the interstory drift values attained during seismic excitations.

The Italian code prescribes that the interstory drift ratio must not exceed 5%. According to the analysis results, the maximum interstory drift ratio is equal to 4.95%, within the limit value. The maximum interstory drift is experienced at the second story, as reported in Figure 13. This check is crucial to understand that no intervention to reduce displacements is needed. Therefore, the structural stiffness does not need to be increased.



Sism. 1000/H (nodi)

Massimo 4.95

Minimo 0

Figure 13. Colormap of interstory drift values (as ‰ of interstory height, extracted from Pro_SAP software).

4.9.3. Seismic Analysis Results at Life Safety (LS) Limit State

Framed reinforced concrete buildings designed according to outdated codes are often subjected to fragile collapse due to insufficient capacity under shear stresses, affecting beam–column joints, beams, and columns. This does not enable buildings to exploit their ductile capacity. Using a linear analysis method, the LS verification has been carried out by gradually increasing the seismic action (ground acceleration) until the first fragile crisis occurred. The technical literature enables making several assumptions of what failure condition is determining the LS state, especially regarding the number of failed elements. In terms of strictly normative aspects, when the first element fails, the LS limit state is reached. However, during the gradual seismic input intensity increase, often, more elements reach the failure (almost) simultaneously and the result is that the LS state is often represented by the failure of a group of elements. In this case, the building seismic vulnerability is influenced by the beam–column joints' failure.

Safety checks of these elements must be performed (for external joints) according to expression (1) reported in Figure 14, where f_{yd} is the steel yielding stress and A_{s1} is the top beam reinforcement area. V_c is the shear force acting on the column and γ_{rd} is a safety factor. V_{jbd} is the joint shear stress. Due to the fragility of joints, the top reinforcement A_{s1} will not reach the yielding, and considering f_{yd} stress is useless and too conservative in terms of the resulting shear stress on the joint panel. Therefore, in place of f_{yd}, the real tensile stress σ_s acting on the top beam reinforcement may be used (which is much lower), according to Equation (2), in Figure 14.

This enables greatly reducing the number of unchecked joints, preventing overconservative assessments. Following this procedure, the LS limit state seismic acceleration was found and the safety index calculated, as reported in Figure 15a.

In fact, $\zeta_{LS} = 0.1$ indicates that the building structure in the as-built condition is able to sustain only 10% of the design seismic action. At that stage, two beam–column joints and one column member failed under shear. A fully code-conforming structure should have an index value equal to at least 1.0.

In order to obtain an outline of a possible retrofit intervention, the seismic action has been gradually increased. Increasing the seismic action to 50% of the seismic design value, seventeen joints and six column elements failed under shear, as indicated in Figure 15b. It must be noted that, without the assumption of Figure 14, there would be sixty-three failed joints, with severe consequences regarding the retrofit intervention.

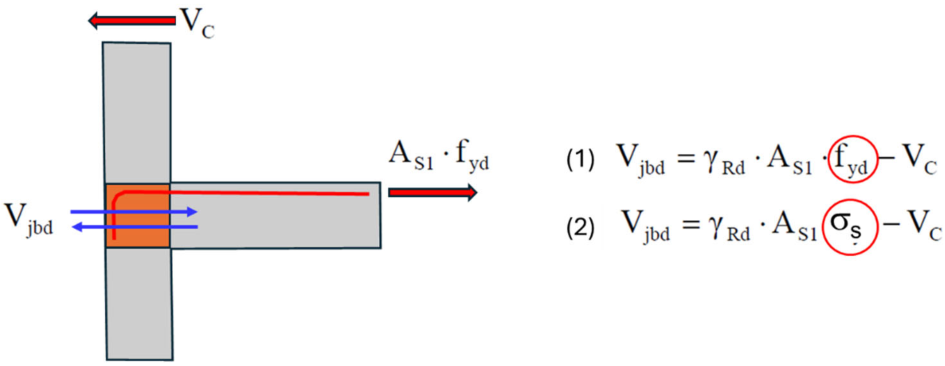
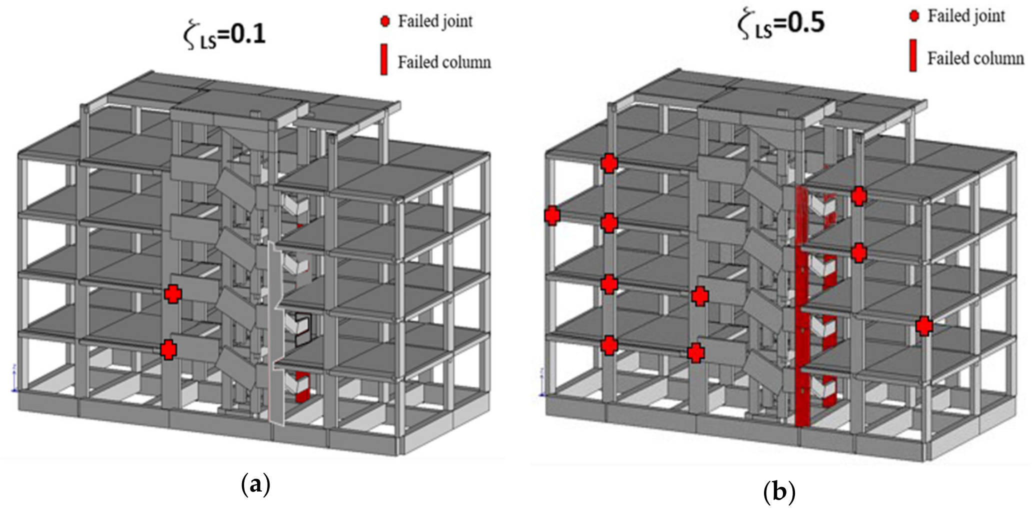


Figure 14. Safety checks of beam–column joints.



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

Figure 15. Safety checks of beam–column joints for ζ_{LS} = 0.1 (**a**) and ζ_{LS} = 0.5 (**b**) (extracted from Pro_SAP software).

For ζ_{LS} values higher than 0.5, flexure failure of the beams and columns began to occur, and more intrusive and impacting interventions would be needed. Therefore, ζ_{LS} = 0.5 is clearly the threshold of the seismic safety index that can be reached by undertaking interventions only on beam–column joints and a few columns placed in the staircase. Moreover, all the failed joints are placed on the building façade, thus enabling the structural interventions implemented via the outside, with minimal intrusiveness in dwellings.

4.10. Detailed Energy Audit

The energy audit was carried out through an analysis of the actual consumption in the current state of the building–plant system. The objective is to define a baseline consumption to be used for the evaluation of the energy improvement interventions. In this way, actions on the envelope and on thermal and electrical systems can be defined. These actions can be completed through monitoring systems and integrated with renewable sources.

The energy audit was realized using the TerMus BIM tool, 52.00e Version [31], a commercial software produced by ACCA software S.p.A. The starting point was the creation of the BIM model of the IDSB.

In Figures 16 and 17, the created three-dimensional model is shown.

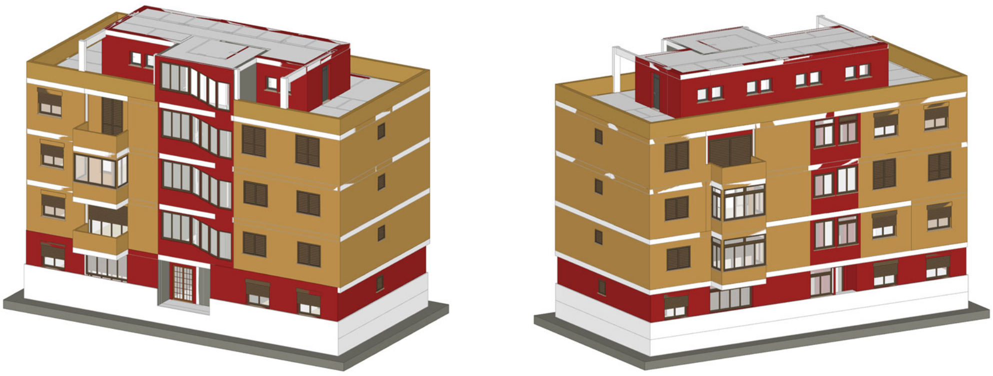

(**a**) (**b**)

Figure 16. The three-dimensional model: (**a**) east view and (**b**) west view (extracted from TerMus BIM software, 52.00e version).

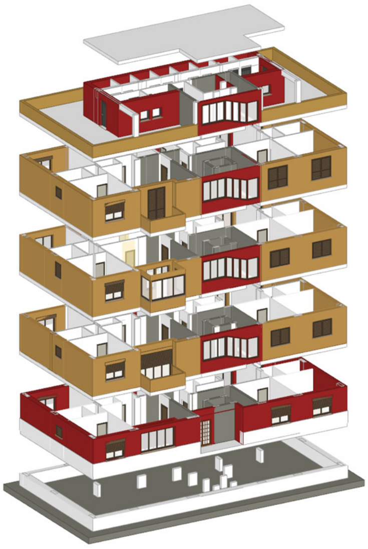
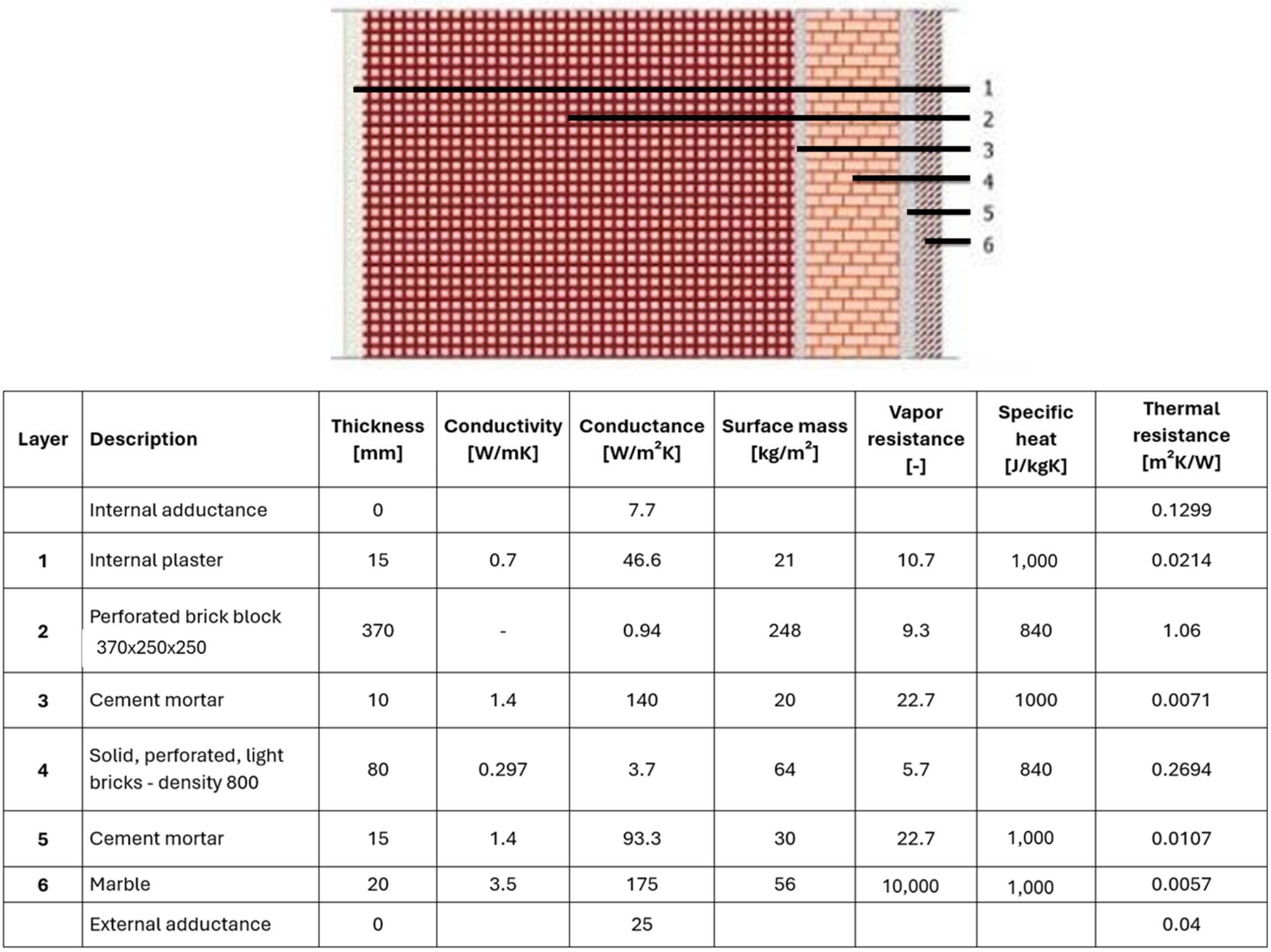


Figure 17. Vertical building development (extracted from TerMus BIM software, 52.00e version).

The transmittance, used in the simulation software, was calculated from the results of the coring tests performed on the wall package. In Figure 18, two wall packages are evidenced.

Figure 18. Results of the coring tests and visual inspections.

The stratigraphy is visible from the coring tests, and four types of infills were considered and modeled in the TerMus software. Figure 19 shows the detailed stratigraphy of the envelope wall equipped with marble cladding, located at the building base, while Table 5 shows the physical characteristics assumed in the energy audit.



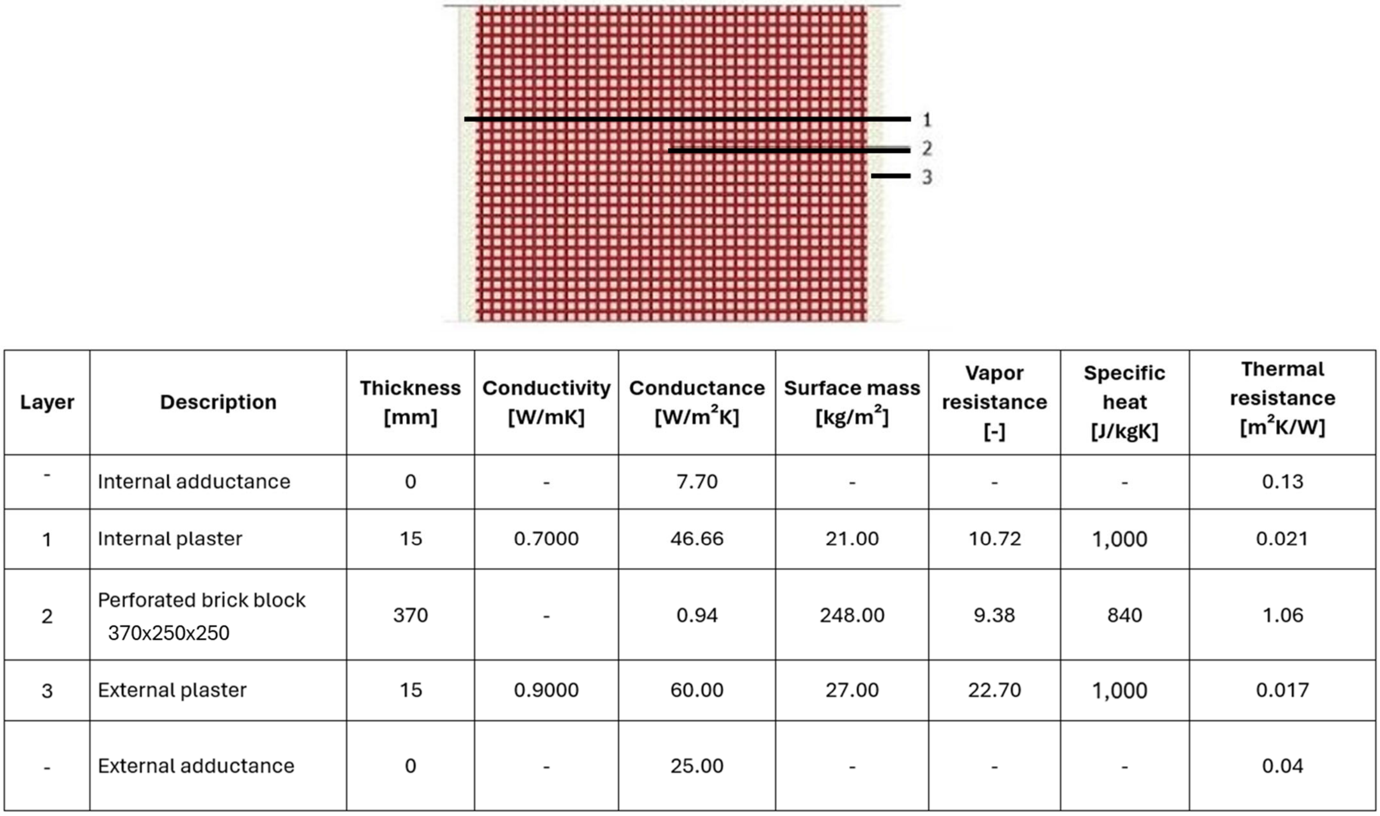
Layer	Description	Thickness [mm]	Conductivity [W/mK]	Conductance [W/m²K]	Surface mass [kg/m²]	Vapor resistance [-]	Specific heat [J/kgK]	Thermal resistance [m²K/W]
	Internal adductance	0		7.7				0.1299
1	Internal plaster	15	0.7	46.6	21	10.7	1,000	0.0214
2	Perforated brick block 370x250x250	370	-	0.94	248	9.3	840	1.06
3	Cement mortar	10	1.4	140	20	22.7	1000	0.0071
4	Solid, perforated, light bricks - density 800	80	0.297	3.7	64	5.7	840	0.2694
5	Cement mortar	15	1.4	93.3	30	22.7	1,000	0.0107
6	Marble	20	3.5	175	56	10,000	1,000	0.0057
	External adductance	0		25				0.04

Figure 19. Detailed stratigraphy of the envelope infill wall with marble cladding (adapted from TerMus BIM software).

Table 5. Thermal features of the envelope wall with marble cladding.

Parameter	Value	Unit
Total thickness	510	mm
Global thermal transmittance	0.65	W/m^2K
Global thermal resistance	1.54	m^2K/W
Global surface mass	418.00	kg/m^2
Areic heat capacity	45.38	kJ/m^2K
Periodic thermal transmittance	0.10	W/m^2K
Attenuation factor	0.16	-
Phase shift	14.21	h

Figure 20 shows the detailed stratigraphy of the general envelope wall composed only of perforated blocks with plaster inside and outside, used in most of the building's perimeter walls.



Layer	Description	Thickness [mm]	Conductivity [W/mK]	Conductance [W/m^{2}K]	Surface mass [kg/m^2]	Vapor resistance [-]	Specific heat [J/kgK]	Thermal resistance [m^{2}K/W]
-	Internal adductance	0	-	7.70	-	-	-	0.13
1	Internal plaster	15	0.7000	46.66	21.00	10.72	1,000	0.021
2	Perforated brick block 370x250x250	370	-	0.94	248.00	9.38	840	1.06
3	External plaster	15	0.9000	60.00	27.00	22.70	1,000	0.017
-	External adductance	0	-	25.00	-	-	-	0.04

Figure 20. Detailed stratigraphy of the general envelope infill wall (adapted from TerMus BIM software).

As a result, Table 6 shows the physical characteristics assumed in the energy audit. The other two types of envelope walls are not shown here since they are used in small envelope parts and do not significantly influence the energy behavior of the building, even though they were fully considered in the model.

Table 6. Thermal features of the general envelope wall.

Parameter	Value	Unit
Total thickness	400	mm
Global thermal transmittance	0.78	W/m^{2}K
Global thermal resistance	1.27	m^{2}K/W
Global surface mass	248.00	kg/m^2
Areic heat capacity	48.29	kJ/m^{2}K
Periodic thermal transmittance	0.25	W/m^{2}K
Attenuation factor	0.31	-
Phase shift	10.25	h

A survey on the heating systems was carried out. It found that all the apartments are equipped with an independent heating system. Five dwellings have a condensing boiler, while the remaining units have a standard boiler. Three apartments have an air conditioning system with a heat pump. It can also be used as a heating system. No thermostats or building automation and control devices are present. The unique device is a switch to turn the heating on and off. Furthermore, no mechanical ventilation systems are present. It is difficult to define the energy class of the household appliances, excluding one apartment, which was recently renovated (major renovation).

The consumption data were obtained through the customer service of local distributors (Figure 21). In particular, for electricity, we received data from Enel Distribuzione and data for natural gas from Italgas. These data were entered into the model by dividing the information for each individual apartment.

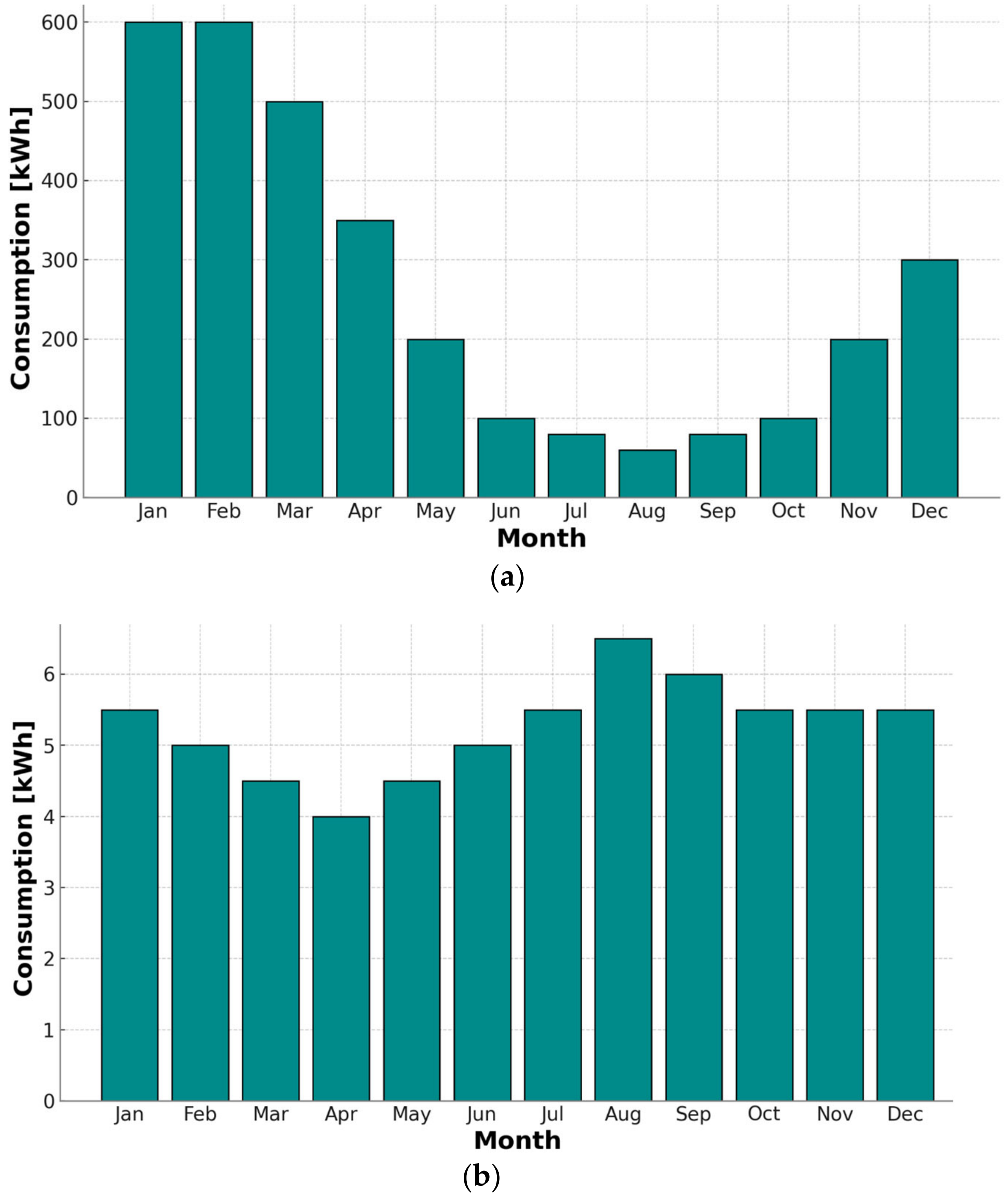


Figure 21. (**a**) Natural gas and (**b**) electricity consumption over one year (adapted from TerMus BIM software).

This procedure required the validation of the numerical model since the actual consumption was not aligned with the estimates by the software according to the current regulations.

This aspect is due to the fact that the regulations, for climate zone C, stipulate an on-time period for heating that runs from November 15th to March 31st and an on-time period for cooling that runs from June 10th to September 4th (Figure 22), while, in reality, based on the information provided by the tenants, the operation periods do not coincide with those in the regulations but are related to the habits of the tenants.

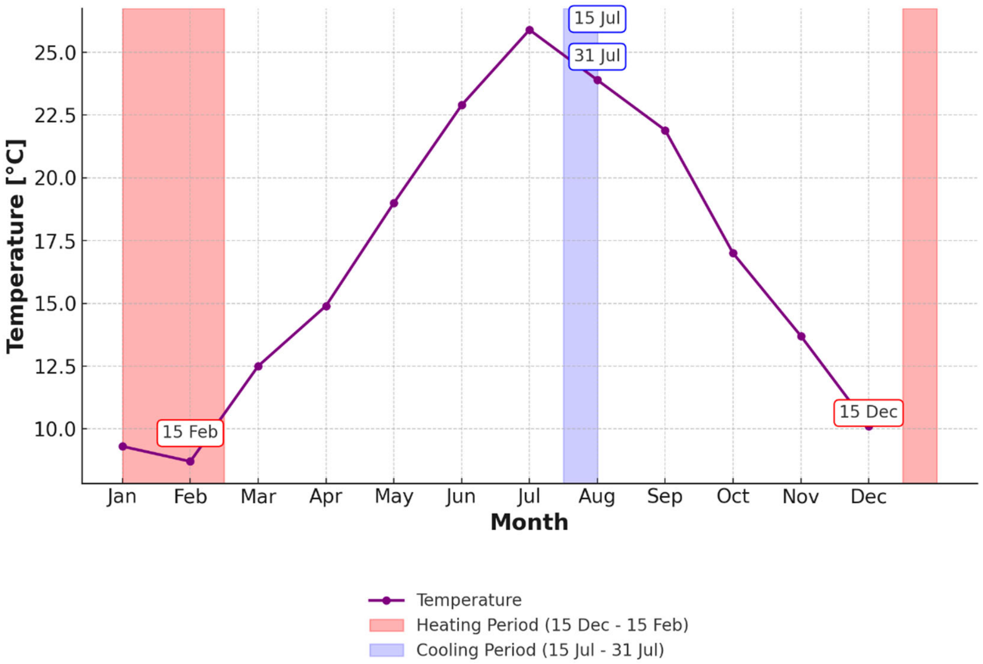
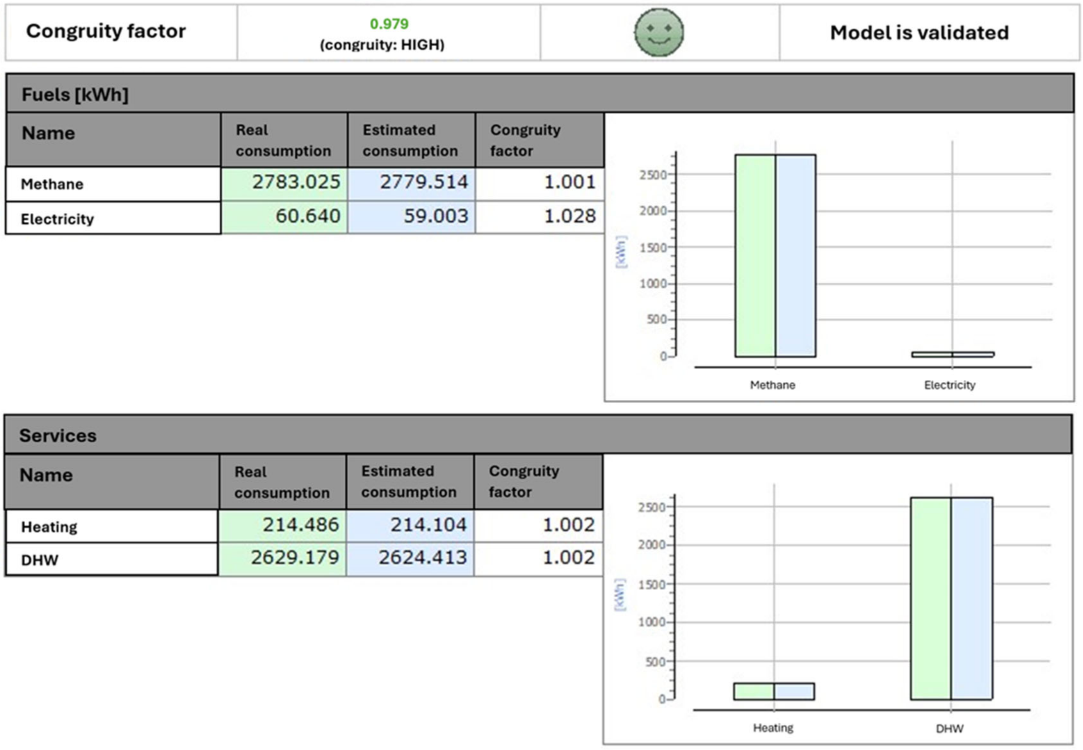


Figure 22. Regulation of the operating periods of air conditioning systems for an apartment (adapted from TerMus BIM software).

Therefore, to calibrate the model, a consumption analysis was carried out, acting, for each apartment, on the turn-on period of the winter and summer air conditioning systems, as in Figure 23.



Congruity factor	0.979 (congruity: HIGH)		**Model is validated**

Fuels [kWh]

Name	Real consumption	Estimated consumption	Congruity factor
Methane	2783.025	2779.514	1.001
Electricity	60.640	59.003	1.028

Services

Name	Real consumption	Estimated consumption	Congruity factor
Heating	214.486	214.104	1.002
DHW	2629.179	2624.413	1.002

Figure 23. Model validation (adapted from TerMus BIM software).

In Figure 23, the positive validation of the calculation model is shown, with a congruity factor of 0.979.

In the next year, an integration of the numerical model will be conducted by introducing a series of upgrading interventions with the aim of making the building energy-efficient. In particular, it is planned to create thermal insulation of the building envelope, replacing the external windows and doors, providing the building with energy autonomy through the use of energy production systems from renewable sources (vertical PV panels) and introducing a centralized thermal generation system based on innovative storage technologies, protected by patent. This model will enable a technical/economic evaluation to be carried out, which will provide designers with essential information for design choices.

In the future, as soon as the TerMus software allows it, dynamic hourly calculations will be carried out, enabling the optimization of the operation of the thermal generators.

5. Discussion of Results

The integrated methodology presented in this case study demonstrates both the challenges and opportunities in conducting comprehensive building assessments while minimizing disruption to occupants. It clearly emerges that, to optimize the process in terms of determining the actual condition of the building to be renovated, it is necessary (i) to perform integrated planning of the measurements and to identify all the information required in terms of both the structural and energy aspects, which also means lowering the costs; (ii) to reduce as much as possible the number of inspections and minimize the disturbance to the tenants; and (iii) to carry out interviews with the tenants during technical inspections so as to obtain more complete information on the building's history. In particular, several key findings are evidenced from this research, which have important implications for future renovation projects of inhabited social housing buildings. First, the combination of non-destructive testing (NDT) with limited destructive testing proved to be highly effective in achieving the required knowledge level (KL2) while maintaining social acceptability. The strategic use of sonic measurements to guide core extraction locations represents a particularly valuable approach as it enabled optimal sampling while minimizing the number of invasive tests. This methodology could serve as a model for similar assessments of inhabited buildings where extensive destructive testing is impractical.

The structural assessment revealed that, while the building performs adequately under gravity loads (C/D ratios > 1.0), it exhibits significant seismic vulnerabilities, particularly in beam–column joints. The finding that the structure can sustain only 10% of the design seismic action ($\zeta_{LS} = 0.1$) underscores the urgent need for seismic upgrading. However, the analysis also showed that a reasonable improvement to $\zeta_{LS} = 0.5$ could be achieved through interventions focused primarily on exterior joints and select columns, enabling the renovation work to be conducted largely from outside the building. This finding has significant practical implications for renovation planning as it suggests that meaningful seismic improvements can be achieved without extensive interior modifications that would severely impact the residents.

From an energy perspective, the audit methodology highlighted the importance of calibrating theoretical models with actual consumption data. The significant discrepancy between the regulated operating periods and actual usage patterns demonstrates that the standard assumptions may not accurately reflect the real-world conditions in social housing. The achieved model validation factor of 0.979 confirms that incorporating actual usage patterns is essential for realistic energy performance assessment.

The participatory approach, involving questionnaires and face-to-face interviews with residents, proved to be invaluable in gathering accurate information about the building usage patterns and identifying the critical areas for investigation. This social component of the methodology not only improved the technical assessment's accuracy but also facilitated resident cooperation during the investigation phase. The role of a "social facilitator" emerged as a crucial element in bridging the gap between the technical experts and residents.

A key limitation of the current study is the reliance on steady-state energy modeling, which may not fully capture the dynamic behavior of the building–plant system. Future work should incorporate hourly dynamic calculations when the software capabilities permit, potentially leading to more optimized renovation solutions. Additionally, while the methodology successfully balanced the technical requirements and social considerations, further research could explore ways to further reduce the invasiveness of structural investigations while maintaining assessment accuracy.

The findings suggest that future renovation projects should adopt similarly integrated approaches that consider structural, energy, and social aspects simultaneously. This holistic perspective is essential for developing renovation solutions that are not only technically sound but also practically implementable in occupied buildings. The methodology demonstrated here could be particularly valuable for the large-scale renovation programs needed to achieve climate and seismic resilience goals in Europe's aging social housing stock.

6. Conclusions

This study presents a pioneering integrated assessment methodology for social housing renovation, demonstrated through a case study in southern Italy as part of the REHOUSE Project. The research makes several significant contributions to the field of building renovation, particularly in the context of inhabited social housing.

The innovative aspect of this work lies in its holistic integration of structural, energy, and social considerations within a single assessment framework. While previous approaches have typically treated these aspects separately, our methodology demonstrates that their integration not only improves technical outcomes but also enhances the feasibility of renovation interventions in occupied buildings.

The effectiveness of combining non-destructive testing with strategic destructive sampling, guided by sonic measurements, proved to be particularly valuable. This approach successfully achieved the required knowledge level (KL2) while minimizing disruption to residents. Moreover, detailed indications were provided to carry out a preliminary structural evaluation through the Condomini+ 4.0 app, which suggested undertaking a detailed assessment according to the structural code in force in Italy. Importantly, the structural analysis showed that meaningful improvements (up to ζ_{LS} = 0.5) could be achieved through primarily external interventions, making the renovation process more feasible for occupied buildings.

The energy audit methodology highlighted the critical importance of calibrating theoretical models with actual consumption patterns. The achieved validation factor of 0.979 demonstrates that incorporating real usage patterns, obtained through resident engagement, is essential for accurate energy performance assessment. This finding challenges the adequacy of the standard assumptions in social housing contexts and emphasizes the need for user-centered approaches in energy modeling.

The social component of the methodology, implemented through questionnaires, face-to-face interviews, and the involvement of a social facilitator, proved to be crucial in multiple ways. It not only improved the accuracy of the technical assessments but also facilitated resident cooperation and understanding of the renovation process, which is often a neglected aspect of building renovation projects.

The 10-step REHOUSE integrated assessment methodology (RIAM) developed through this research offers a standardized, replicable procedure for assessing existing buildings, particularly those housing vulnerable groups in social housing contexts. Its success in balancing technical requirements with social considerations makes it a valuable tool for large-scale renovation programs aimed at improving both the seismic resilience and energy efficiency of Europe's aging building stock. Future applications of this methodology could benefit from incorporating dynamic energy modeling and further refinements to reduce the invasiveness of structural investigations. Nevertheless, the current framework represents a significant step forward in developing practical, socially conscious approaches to building renovation that can be effectively implemented in occupied buildings.

Future research should focus on further minimizing the invasiveness of building assessments, particularly for structural and non-structural investigations. This could be achieved by developing and calibrating methods that reduce disruption to occupants while maintaining assessment accuracy. Such advancements would be especially valuable for critical public facilities like schools and hospitals, where continuous operation must be maintained during assessment and renovation activities. The lessons learned from this social housing case study could inform the development of specialized protocols for these sensitive facilities, where both technical rigor and minimal disruption are paramount.

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