


Article

Knowledge-Based Investigation of Seismic Vulnerability Assessment and Compatible Strengthening Design of an Existing Masonry Building

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Abstract: Most existing masonry buildings were built without following code regulations for seismic criteria. Hence, their performance compared to the demands of the current codes, for both seismic and static actions, could be very low. In engineering practice, strengthening interventions can be pursued at different levels, based on qualitative assessments of masonry structures. Firstly, the structures are evaluated through in situ inspections. Then, based on the structural system of the building a strengthening design is proposed. The design can be targeted at guaranteeing a box behavior of structures acting through macro-elements, or at strengthening the in-plane capacity of piers and spandrels. However, lower cognitive levels may drive inaccurate impressions about the capacity of structures, leading to unreliable strengthening solutions. While in some cases the confidence factor could underestimate the effects of the reinforcements, in other cases lower knowledge levels could lead to incorrect reinforcements that do not provide helpful solutions. In this paper, the issues concerning the strengthening design of masonry structures are presented and discussed with regard to an existing building. The construction is a 20th century masonry building used as a nursing home for elderly persons. The study follows a knowledge-based procedure where, after achievement of the highest knowledge level and the proposal of compatible and effective strengthening interventions, the analysis of the potential effects of achieving lower knowledge levels is discussed both in terms of vulnerability computations and in terms of strengthening effectiveness. Regarding vulnerability assessment, a lower knowledge level leads to non-conservative results, with an increase in the estimated capacity of around 80%. Critical evaluation of the different configurations for the case study makes it clear that for the considered masonry building the mortar investigation represented the most important parameter to be investigated. The proposal of strengthening interventions before assessment of this parameter may lead to ineffective improvements resulting in index values lower than 0.60. The study represents the opportunity to assess comparisons in the setting of different investigation strategies and their effect on the definition of the strengthening solutions.

Keywords: existing buildings; destructive campaigns; dynamic identification; structural modelling; seismic analysis



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1. Introduction

In the structural evaluation of existing masonry buildings, understanding the structural system is crucial for quantification of the risk affecting the goods. Referring to masonry structures, during ground motion old constructions tend to behave following two distinct and complementary penchants: out-of-plane versus in-plane [1]. This distinction does not only apply to the direction of the seismic action but is also related to the general capacity of masonry structures to exhibit a global behavior. The so-called *box behavior* is assumed when the individual parts of a masonry structure are able to cooperatively participate in the structural performance of the system [1,2]. To this aim, it is important that the

orthogonal connections within walls are solid and follow good workmanship practices. In addition, the slabs should be rigid or semi-rigid, distributing the seismic forces among the different piers. Conversely, local behaviors are exhibited; the building components tend to highlight major distinctions, with parts behaving separately and independently during ground motion. These parts are later identified as macro-elements. Post-earthquake damage evidence indicates the occurrence of both phenomena [2–7], although the building-by-building specificities and peculiar taxonomies of masonry structures can be assumed based on the years in which masonry structures were constructed [2,8,9].

Aiming to investigate a specific building, the case study itself represents a good example, containing all the information for its evaluation. Different numerical approaches have been defined to investigate the structural performance of masonry buildings [10,11]. In this context, selection of the most suitable approach for the structural investigation is driven by understanding the resistant system of the structures. The “knowledge path” recommended by codes to investigate the existing buildings can be adopted. The knowledge path involves both the understanding of the acting resistant system and the definition of the mechanical properties of the adopted materials. The first topic can be covered by combining research on the historical evolution of the building, together with accurate geometrical structural surveys. Hence, the second point requires establishing a diagnostic campaign that uses partially destructive techniques to identify the mechanical properties of the materials. In the structural assessment of existing buildings, three specific knowledge levels (KL1, KL2 and KL3) are defined [12–14]. These are based on the information collected about the identified structural system. For each KL, a relative confident factor (CF) is employed to reduce the mechanical properties previously defined in order to adopt the semi-probabilistic approach of the codes [15]. KLs are generally three, from KL1, the lowest level achievable, to KL3, which requires achievement of exhaustive knowledge about structures and mechanical quality of the materials. The CFs follow an empirical rule that is inversely proportional to the obtained knowledge. For example, KL1 corresponds to a CF of 1.35, whereas the value is 1.20 for KL2 and 1.00 for KL3. In the case of masonry structures, in the absence of specific in situ characterizations, a list of mechanical parameters listed in the Italian recommendations [14] can be adopted (Table C8.5.I). For KL1, the code specifies use of the mean values for the elastic moduli and the minimum values for resistances. In addition, Table C8.5.II indicates the improvement coefficients that can be used in case of good masonry qualities, as for the evaluation of strengthening solutions. Referring to masonry structures, the common rule is that the characterization of the mortar is enough to achieve a KL2, while KL3 is achieved by executing destructive tests such as double flat-jack test for the Elastic Young’s modulus and the diagonal test for Shear modulus. However, authors developing different probabilistic frameworks have proven the feeble reliability of the KLs for robust structural assessment of buildings [16–18]. In this regard, the initial parameters coming from MIT2019 can be implemented according to a Bayesian approach [16,19–21]. The determination of reliable structural models characterized with proper mechanical values is not only important to determine the safety level of a structure, but it also concerns evaluation of the strengthening solutions to be proposed [22–24].

Concerning masonry structures, different strengthening interventions have been defined previously, and several contributions are aimed at the presentation and a critical comparison based on the effectiveness of different solutions [23,25–28]. According to Yavartanoo and Kang (2022) [23], this can be divided into three categories, i.e., inventions targeted at improving the structural integrity, reducing the seismic demands, and upgrading the structural elements of the existing building. Within the first categories, different interventions are available in the market. These systems can be related to traditional as well as contemporary techniques (insertion of tie rods, strengthening by using fiber-reinforced textures) [29–34]. The proposed interventions lead to an investigation of the structural capacity of the building, where the deficiencies can relate to: (i) poor capacity of the masonry walls due to poor mortar capacity or absence of transversal elements; (ii) lack of connections between orthogonal walls; and (iii) necessity of increasing the mechanical properties of

masonry walls. For the first case, mortar regeneration through injections or transversal anchorage systems can be adopted, whereas a second technique can take advantage of both metallic elements and fiber strips [35,36]. In the second case, different interventions aimed at guaranteeing a box behavior can be proposed. Among them, insertion of ring beams and stiffening the membranes of the structure are the most common strategies [28,37]. The third case is similar to the first, varying only according to the purpose of the improvement. A wide array of contributions is devoted to strengthening the masonry walls through external application of reinforcements. At first, bi-directional steel grids embedded into concrete coats were proposed; however, these applications are being replaced with use of more compatible solutions that increase the ductility of masonry panels without altering the general stiffness of the structural system by using composite materials [38]. Nowadays, several contributions are targeted at increasing multiple aspects through integrated procedures improving the seismic and the thermal capacities of structures [39–41]. Another important aspect that it is worth mentioning regards the initial state of the building, since only the effective deficiencies of a structure can lead to mitigation of its vulnerabilities. Hence, in the case of a system not guaranteeing a box behavior, the first proposal should be oriented at this achievement by proposing solid connections between orthogonal walls and stiffening of the existing slabs. In recent times, the interventions have not always been consequent to significant cognitive procedures. On the contrary, professionals promoted critical seismic interventions using RC structures in combination with the pre-existing construction. The outcomes of these approaches have shown bad results. In many cases, the addition of weight and rigid elements (such as slabs or roof) inside delicate bearing wall systems characterized by poor mortar capacities has led to major collapse of these construction, promoting collapse mechanisms similar to the “pancake collapse” of RC constructions [42,43].

In this paper, the issues related to the definitions of comparable strengthening approaches are presented and discussed in relation to a nursing home for elderly persons located in the municipality of Bucine, in Tuscany (IT). The building represents a standard regular masonry construction with architectural features similar to many other structures representative of schools all over Italy; therefore, some general outcomes for similar masonry constructions may be found. The design proposal has taken advantage of an exhaustive knowledge path, whose influence is then evaluated for the proposal of compatible interventions. The interventions are later discussed in terms of potentiality with respect to the different achievable knowledge levels. The line of research of this paper is oriented to critical evaluation of non-reliable strengthening solutions following the achievement of non-exhaustive cognitive levels. The contribution warns about the critical issues related to limited diagnostic campaigns, aimed at highlighting the relevance of proper cognitive research for the proposal of compatible and effective interventions.

2. Knowledge-Based Procedure

2.1. The Case Study

The investigated building is a masonry structure located in Bucine, in the province of Arezzo (IT). The building serves as a nursing home for elderly people (Figure 1). More specifically, the investigated structure is the oldest construction of a cluster of four distinct buildings identified as *Residenza socio assistenziale*. The current structure has clinics and offices; the other two structures of reinforced concrete (RC) are designated as residential spaces for the patients. Finally, a fourth building houses a gym and mortuary chapel of the complex. The masonry building is characterized by a regular architectonical disposition in plan and in height. Historical research dates its erection to the 1930s, when it served as a kindergarten. The construction is characterized by a regular architectural disposition. The building has a semi-underground level, a ground level and a first floor. The plan is symmetrical with respect to the entrance, where the staircase permits access to the upper level.

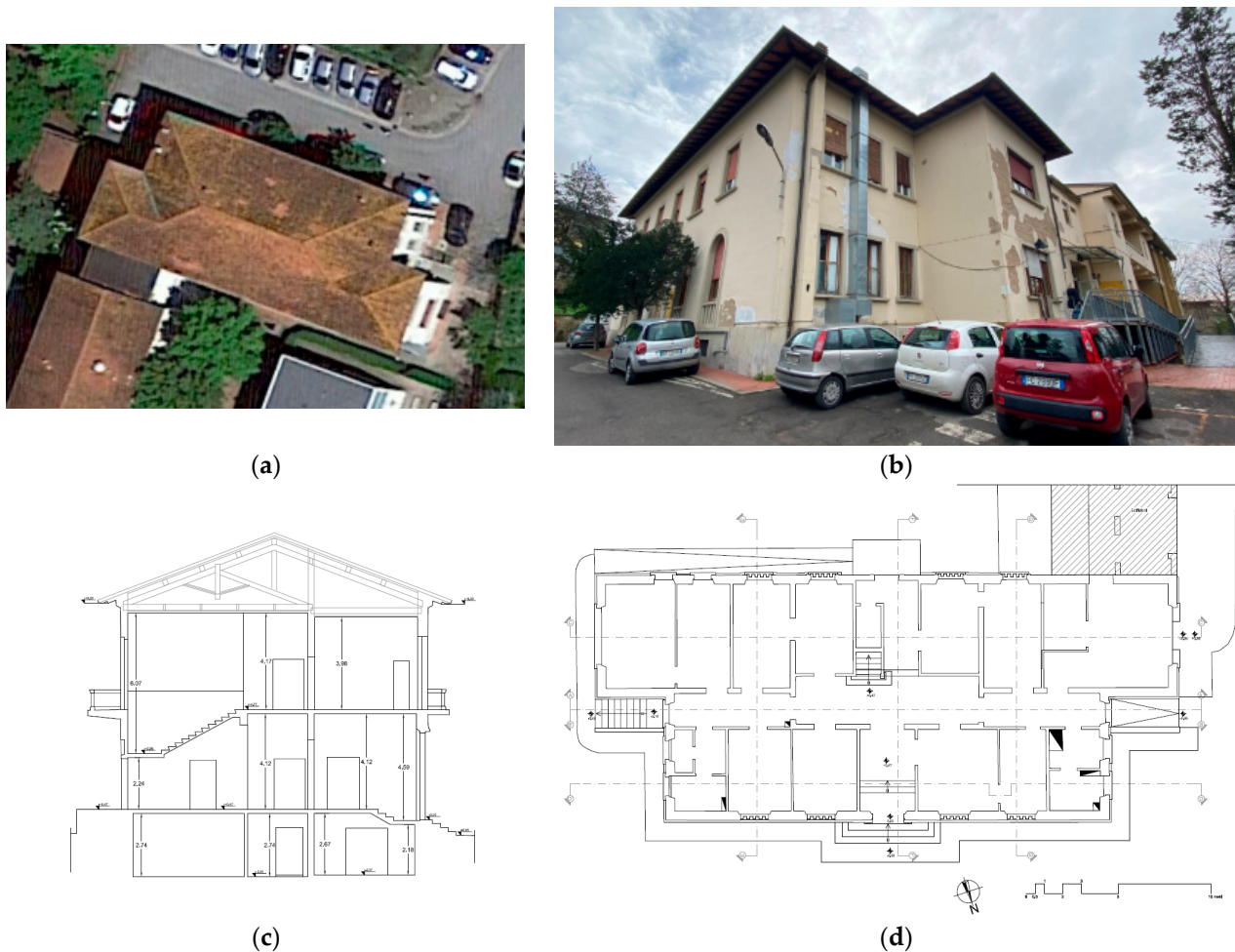


Figure 1. (a) Areal view of the building; (b) image of the structure from the street; (c) architectural transversal section of the construction; (d) ground floor plan.

2.2. Exhaustive Knowledge Acquisition: KL3

The masonry building has been the object of a significant knowledge campaign targeted at achieving the highest KL defined by the Italian code, i.e., KL3. To this aim, several investigations and techniques have been conducted, as summarized in Table 1. Remote sensing laser scanning of the whole building was executed to ascertain the architectural consistency of the building in its current state with a high level of accuracy. The laser scanning survey was used to obtain a 3D point cloud which was later used to extract bidimensional drawings of the construction (plans, sections). Diagnostic campaigns have been executed to reveal the structural features of the construction. In this perspective, a hierarchical approach has been adopted. Initially, non-destructive (ND) tests were widely executed in order to globally identify the structural elements of the building. Thermography and ground penetrating radar (GPR) were employed to characterize the structural system of the building. When combined, these tests provide useful information to non-invasively characterize masonry and historical constructions [20,44,45]. The hypothesis made on the basis of the interpolation of the two ND tests was later validated by excavating 16 test holes, which have permitted unequivocal identification of the structure of the buildings. Furthermore, visual inspections with an endoscopy have been conducted to investigate the inner layers of horizontal and vertical elements.

These methods enable us to define the structural system of the building. The bearing walls of the structure are characterized by rough-block stone masonry for the external panels, with clay brick masonry for the internal partitions (Figure 2). The internal structural walls are made of one single brick layer, leading to particularly slender panels. The external

bearing walls in stone masonry are enriched by the presence of horizontal courses of bricks. The slabs are characterized by RC joists alternated with hollow clay elements, the so-called *solai in latero-cemento*, typical of the modern Italian tradition. Except for the roof, the connection between walls and slabs is characterized by the presence of a concrete ring beam, distributing the load and leading to a box behavior. The ceiling of the roof is made of a clay structure suspended over timber beams (the so-called Perret ceiling), representing a very fragile element. Finally, the roof is a wooden structure covered by clay roof tiles in a traditional Italian fashion.

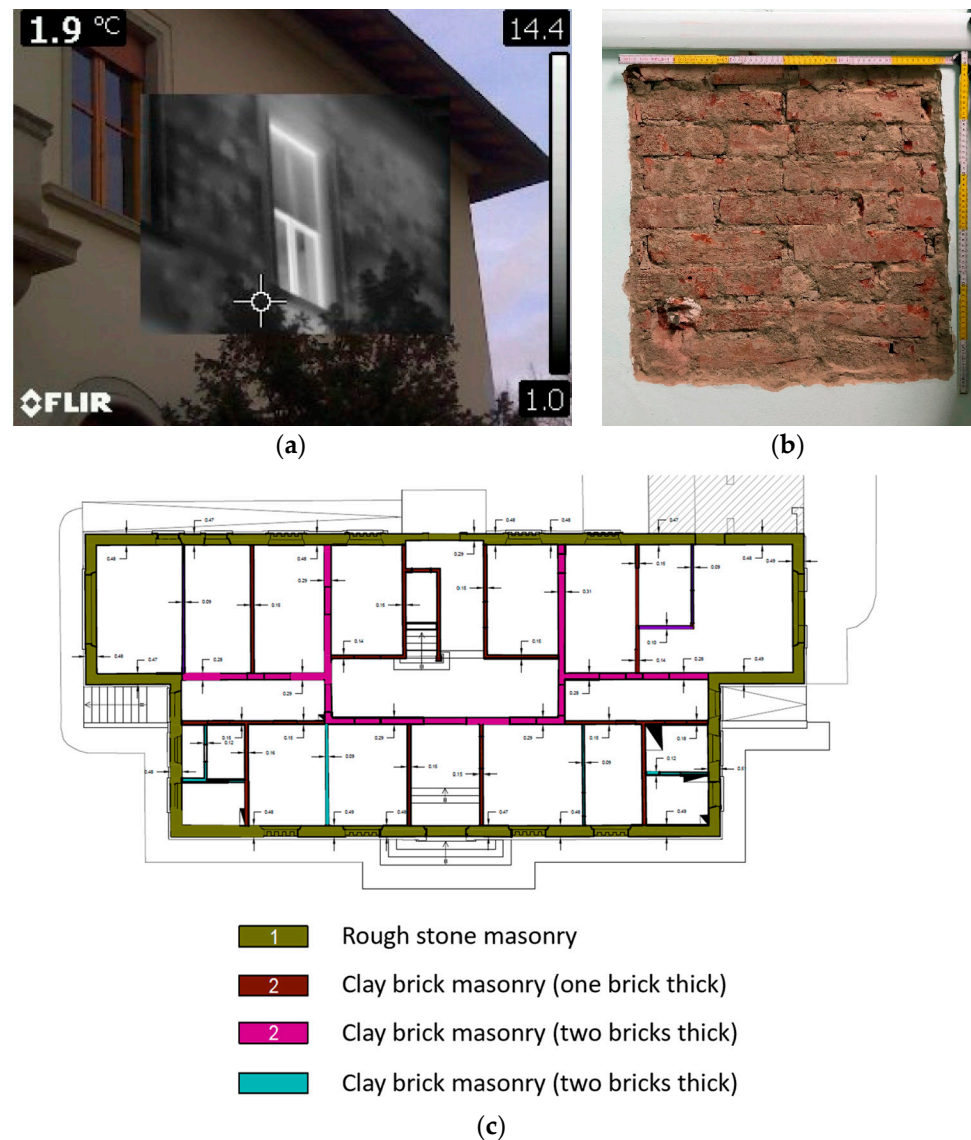


Figure 2. (a) Thermography investigations; (b) test holes on a clay masonry wall; (c) structural characterization of masonry walls.

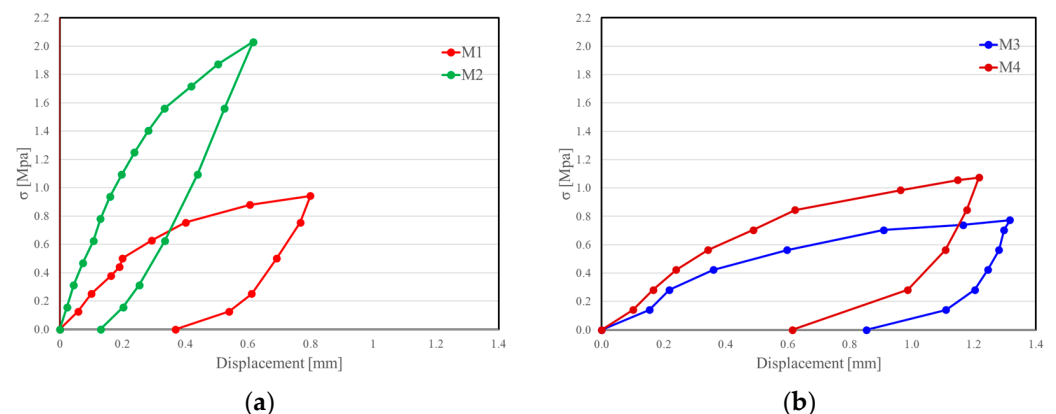
Later, destructive analyses were carried out to characterize the mechanical value of the elements. The investigations focused on load bearing wall structures and the concrete composition of the slabs. Regarding the masonry walls, the analyses assessed the integrity of the masonry and the different components (mortar + resistant elements). Details of the investigations conducted are shown in Table 1.

Table 1. Investigations conducted on the building.

Knowledge Level 3	KL3	
Architectural survey	Complete	Laser scanning survey
Structural characterization	Complete	Thermography campaign GPR survey Trial holes + endoscopy
Mortar characterization	Accurate	Mineralogic + petrographic analysis Drilling tests
Elastic Young's modulus	In situ	Double flat-jack test
Shear resistance	In situ	Shove test
Compressive strength on the resistant elements	Laboratory	Compressive test
Compressive strength of the concrete	Laboratory	Uni-axial compressive test
Confidence Factor	CF3	1.00

Considering the entire masonry panels, double flat-jack tests targeted at defining the Elastic Young's Moduli and shove tests for shear resistance were executed.

For the double flat-jack tests, four tests were performed, two for each masonry typology (Figure 3). The results are shown in Table 2.

**Figure 3.** Double flat-jack results for the two masonry types according to the four executed tests: (a) clay brick masonry; (b) rough-block stone masonry.**Table 2.** Destructive tests executed at the masonry panel scale.

		Clay Brick Masonry		Rough-Block Stone Masonry	
		M1	M2	M3	M4
Flat-jack test	E (MPa)	1194	2952	603	869
Shove test	τ_0 (MPa)	0.165	0.403	0.013	-
	μ (-)	0.144	0.259	0.022	-

Referring to the mechanical values, the obtained parameters were compared with the ranges provided by MIT 2019 [14] for the same masonry typologies. Except for M2, which specifies bigger values, all tests denounce values of Elastic Young's Modulus lower than the minimum range of the code (rough-block stone masonry 1020–1440 MPa, clay brick masonry 1200–1800 MPa, respectively). For the clay brick masonry, it is worth noting that

the two tests provide a mean value equal to 2073 MPa, which is higher than the maximum value assumed for general masonry.

Two shove tests were executed on the clay elements of the brick masonry, while only one test was performed on the stone masonry. The first two tests provided the mean shear resistance of the clay brick masonry τ_0 and the friction coefficient μ . For the two tests, the τ_0 values were 0.165 and 0.403 MPa (mean value of 0.284 MPa), while the computation of μ led to 0.144 and 0.259, respectively (mean value of 0.403). The test on the stone masonry yielded values of 0.013 MPa for τ_0 and 0.022 for μ .

In addition to these tests executed on the panels, in situ and laboratory tests were conducted on the singular elements composing the masonry panels. Cubic samples extracted from the stones and the clay bricks were shaped and tested in the laboratory (32 and 28 samples, respectively) in order to investigate the compressive strength f_m of the materials (Figure 4). For the stone elements, a mean value around 80 MPa was derived, while for the brick elements, the analysis led to compressive values around 15 MPa with a mean value of 23.1 MPa.

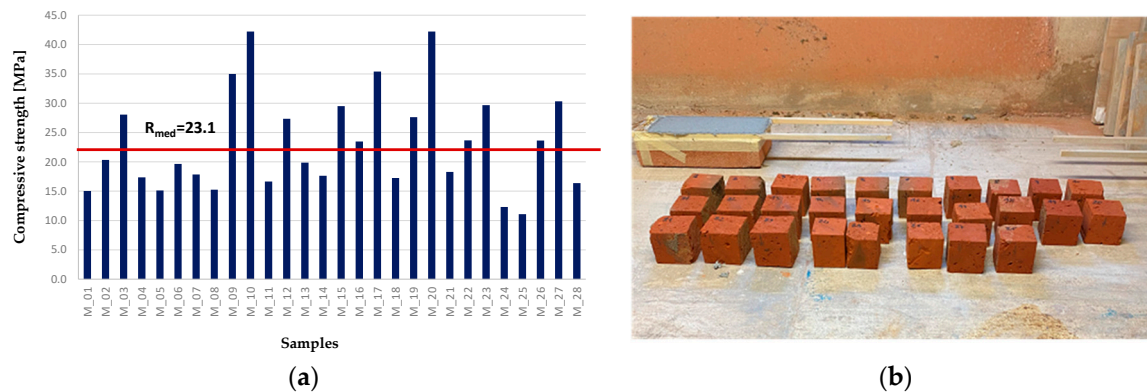


Figure 4. Compressive tests on the cubic samples made by the clay bricks: (a) results of the compressive test; (b) the tested specimens.

Assessment of the mortar involved laboratory analysis and drilling tests. Laboratory tests were conducted on two mortar samples extracted from the two masonry typologies in the building. Mineralogic and petrographic analyses were carried out. The mineralogic tests were performed by X-ray diffractometry using a diffractometer; the petrographic analyses were conducted through an optic microscope. The results of these analyses revealed the composition of the mortar of the masonry panels. They are made of aerial lime produced in the traditional way and characterized by a dimensional ratio between the inert materials and the binders equal to 3 to 1.

In addition, drilling tests on the mortar layers were executed to determine the compressive strength of the element. The tests were performed with a PNT-G penetrometer (Pizzi Instruments). For each test, 15 different trials were conducted, then the mean value of the experiments was considered excluding the minimum and maximum values. The energy released was converted into a resistance value through the Gucci and Barsotti procedure [46]. The drilling tests indicated poor mechanical values for all the executed tests, with resistance strength of the mortar always below 0.70 MPa except for one case (Figure 5). This outcome is particularly relevant in masonry structures where the mortar guarantees the uniform behavior of walls for static and seismic actions. Significantly low mortar values may foretell disaggregation effects during seismic motions, especially in the case of input with an effective vertical component.

Finally, three concrete cores were extracted from the RC ring beams and tested in the laboratory through uniaxial compressive tests. The results of the samples were computed according to the formulation proposed by Masi [47]. The compressive values show a mean resistance of 17.98 MPa.

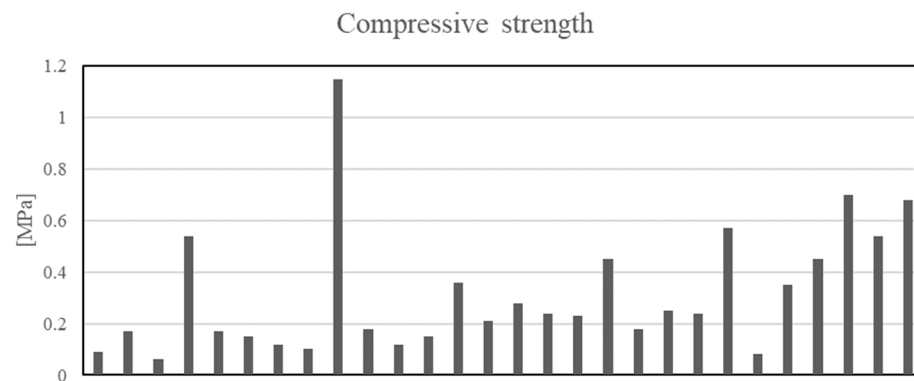


Figure 5. Mortar compressive strength results for the different tests executed in the building. For each test, the result is given by the mean value of 15 experimental acquisitions.

2.3. Seismic Vulnerability Assessment and Multilevel Evaluation

At the end of the acquisition procedure, the seismic vulnerability assessment of the building was carried out. The outcomes of the structural characterization of the construction combined with the obtained mechanical properties can point to the most suitable approach for reliable evaluation. The outcomes of the diagnostic campaigns point out issues that are difficult to be considered in the phases of analysis. Although RC ring beams are present at the ground and first floor levels, no diaphragmatic connection is guaranteed at the roof level. In addition, the delicate and heavy clay Perret roof represents a non-structural vulnerability that could significantly affect the performance of the building under seismic motion. Furthermore, the low mechanical values of the mortar strength may prefigure poor binder capacities that can lead to disaggregation effects (masonry crumbling) [48]. These effects produced by bad mortar properties are not easy to numerically represent, thus pointing out critical issues in the performance of those structures. In the following analysis, a dual approach was used, considering both out-of-plane and in-plane behaviors. The considered local mechanisms involve the top level of the building, as it is the one without perimetral ring beams. On the other hand, global analyses have been considered, since the in situ test holes proved a good connection of the masonry walls. Of course, both approaches are more conservative than assuming a disaggregation effect, which would lead to the “mechanism 0”, anticipating all other types of seismic activity.

For the seismic investigation, the mechanical properties listed in Table 3 were adopted. The properties are based on the Bayesian upgrade of the mechanical values coming from MIT2019 [14] based on the executed tests. For the two masonry typologies, two distinct shear criteria were considered. For the stone masonry, the Turnsek and Cacovic criterion was used, while for the clay masonry the Mohr Coulomb criterion was used. The elastic moduli E were updated on the basis of the double flat-jack tests; hence, the shear moduli G were also updated considering the relationship $G = E/3$. The results of the compressive tests on the resistant elements were considered to upgrade the compressive strength f_m of the masonry types. Considering the results presented in Section 2.2, accounting for values 20% reduced, the interpolations provided by NTC2018 [13] led to a final value of f_m equal to 4.5 MPa for the clay brick masonry. For the stone masonry, as the outcome of the interpolation exceeded the code limits, since the accounted formulations are conceived for artificial elements and not for natural ones, the properties have not been updated according to the executed tests. Finally, the results of the shove tests were adopted to update the τ_0 values for the stone masonry and the f_{v0} value for clay brick masonry. The relationship $f_{v0} = 1.5 \tau_0$ was considered.

In the computation, due to the outcomes of the mortar characterization, the detrimental coefficient equal to 0.80 for the elastic moduli and 0.70 for the resistances were applied, in order to consider the effects of the bad mortar qualities.

Table 3. Mechanical parameters adopted in the two masonry typologies. E represents the Elastic Young's Modulus, G the Shear Modulus, w the specific weight, f_m the compressive strength, τ_0 and f_{v0} the two shear strength values for the Turnsek and Cacovic/Mohr Coulomb criteria, respectively, ϕ the angle of internal friction, and μ the coefficient of internal friction.

Rough-Block Stone Masonry		Clay Brick Masonry	
E (MPa)	947.71	E (MPa)	1827.43
G (MPa)	315.9	G (MPa)	609.14
w (kN/m ³)	20	w (kN/m ³)	18
f_m (N/cm ²)	200	f_m (N/cm ²)	345
τ_0 (N/cm ²)	3.3	f_b (MPa)	23
		f_{v0} (N/cm ²)	31.3
		ϕ	0.5
		μ	0.577

Both approaches of analysis were computed through the software 3Muri (Stadata) [49,50], using the equivalent frame method suite for the global assessment and the macro-element one for the local analyses (Figure 6). Both strategies follow a phenomenological approach where the masonry is discretized according to the experienced damage of the bearing walls. The equivalent frame is conceived for the in-plane behavior of structures, discretizing the masonry panels between piers, spandrels and rigid nodes; this approach been validated by the contribution of different authors especially in the case of regular constructions [51–55]. The macro-element approach follows the assumption that masonry panels behave as rigid blocks connected through kinematic chains. Although the more or less refined available procedures, the methodology is a reliable approach to investigate the structural performance of masonry constructions when the structure of historical discontinuities are pointed out [56–61]. In this work, the seismic demand was needed on the basis of the geological investigation conducted and the hazard information of the area. The different elastic spectra were computed considering an important class equal to III, a nominal life of 50 years and soil class C. For the kinematic analyses, the seismic demand has accounted for the floor spectra which was computed according to MIT2019 [14].

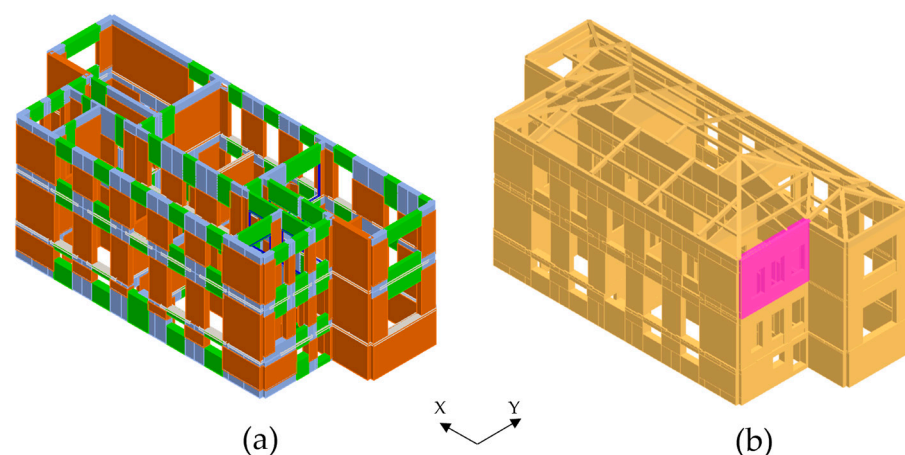


Figure 6. (a) The equivalent frame discretization of the model for global analyses; (b) the macro-element suite for kinematic assessments.

Kinematic analyses were conducted considering the overturning mechanisms of the external facades without accounting for possible restrained capacities given by the friction of the blocks between orthogonal walls. The out-of-plane evaluations both considered the single walls as the corner portions of the building. The analyses concern the computation

of the multiplier indicating the activation of the phenomenon. This coefficient is then converted into a spectral acceleration in order to be compared with the spectra demand of the area. The results of the kinematic analyses lead to capacities significantly lower than the demand at the floor level. In particular, the simple overturning of the masonry facades turns out to be the most vulnerable mechanisms. Within them, the ratios between capacity and demand, the safety index exhibits values lower than 0.60, with the minimum value equal to 0.19. In the kinematic assessment, a CF equal to 1.35 was considered in all the analyses according to the indications provided in MIT [14].

On the other hand, nonlinear static analyses were executed, considering: (i) the global model; and (ii) the in-plane capacity of the single macro-elements. In both strategies the numerical computation was conducted according to two seismic load patterns—one proportional to the masses and one to the inverse triangular. The analyses were conducted along the two main directions, X and Y, and according to the two verses, positive and negative. Further analyses considering the introduction of an accidental eccentricity equal to 5% of the mass were executed for the whole model. In the investigations, the elastic moduli were reduced by 50% to account for the cracked configuration of the masonry as suggested in the codes. The nonlinear static analysis allowed obtaining, for each analysis, a pushover curve defined by plotting the base shear resistance of the building and the horizontal displacement of a control point (selected at the top level of the structure). The pushover curves were then converted into capacity curves for an equivalent single-degree-of-freedom system; the seismic capacity of the structure was computed according to the N2 method [62]. The results for the global assessment indicate inadequate performance of the building. Considering the whole model, the lowest safety index for Life Safety Limit State SLV is equal to 0.445, obtained along the short direction of the structure (Y direction). On the other direction, along the main façade, the minimum safety index value obtained is equal to 0.845, pointing out discrete capacity. The analysis of the masonry walls confirms the same trend. In particular, the worst in-plane capacity is obtained by the right-side wall of the structure, which leads to a safety index of 0.247. In Figure 7, histograms presenting the safety indexes for the non-verified analyses according to the different approaches are shown. In addition to the disaggregation effect, both approaches indicate poor performance of the structure, which requires an adequate strengthening intervention.

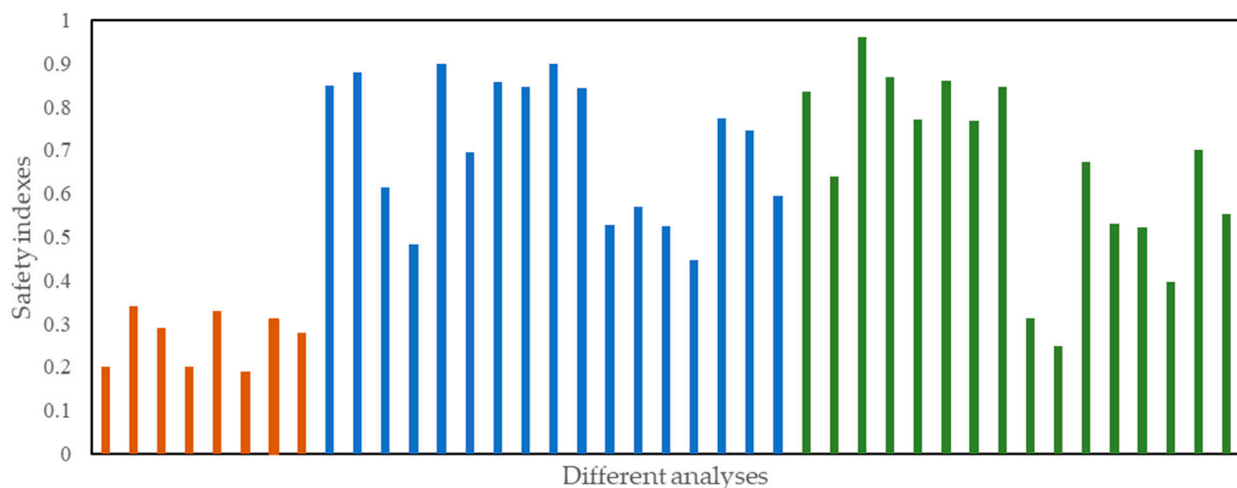


Figure 7. Non-verified safety indexes for the building. Orange bars indicate the indexes obtained through kinematic analysis; blue, the ones obtained through global analyses; green, the ones through pushover analysis on the single walls.

3. Compatible Strengthening Interventions

The investigation has concerned the definition of the structural performance of the building. With this information, compatible and effective strengthening interventions can

be designed. Given the low mechanical properties of the masonries and the mortar layers, the following interventions are proposed:

- mortar regeneration through binder injections inside the core of the masonry walls [34,63];
- masonry confinement through the application of composite reinforced mortar CRM on both sides of the bearing panels [64];
- substitution of the Perret ceiling with insertion of a new steel ring beam, and realization of a light rigid steel frame at the ceiling level;
- addition of a layer of RC slab over the existing latero-cemento slabs to guarantee more rigid diaphragms;
- enlargement of the masonry thickness characterized by an elevated slenderness;
- realization of a light and rigid slab with double-crossed wood over the wooden roof structure to be connected to the ceiling ring beam.

The described interventions have been designed and considered in the seismic improvement. The structural model has been modified and re-run in the new configuration for seismic assessment. For the masonry walls, an improvement coefficient equal to 3.0 for the stone masonry and equal to 1.8 for clay brick masonry have been adopted. The two values are referred to the maximum amplification values available according to MIT2019 in the case of the combination of more techniques (CRM and binder injection).

The strengthened configuration has been tested only through global pushover analysis, assuming that the different interventions guarantee a box behavior. In Figure 8 the performances of the retrofitted structure are presented in terms of capacity curves. It is worth noting that the building shows dual performances, where the inverse triangular mass pattern has the lowest capacities. On the other hand, the construction, due to the disposition of the structural elements along the plan, points out lower performances along the Y directions, which are visible both in terms of initial stiffness and length of the nonlinear branch. The results of the seismic analysis led to safety indexes exceeding 1.0 in the X direction, with a minimum value in the Y direction equal to 0.75. The strengthening intervention induces an increase of the minimum safety index over 0.50, leading to satisfiable performances for an existing structure.

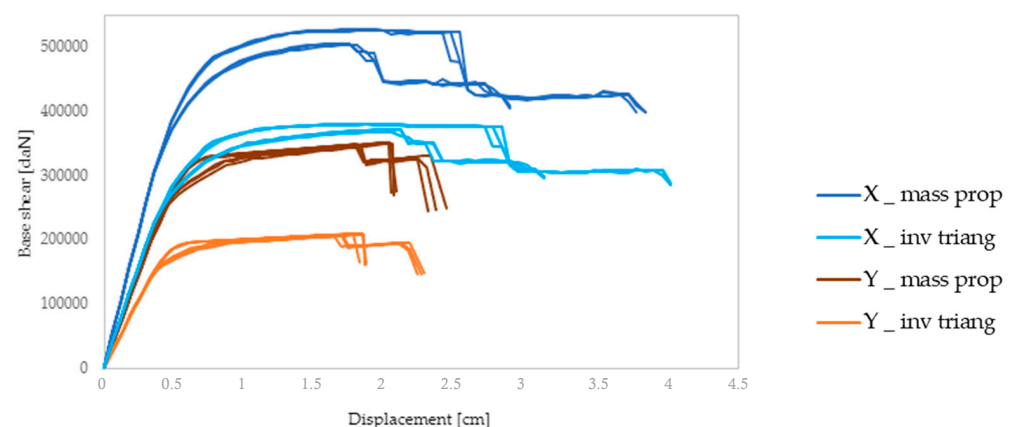


Figure 8. Capacity curves for the retrofitted structure.

3.1. Evaluation Based on Lower KLs

Given these conclusions, the research aims to determine the effects in terms of vulnerability assessment and structural improvements that would have followed the achievement of lower knowledge levels. In Figure 9 a flowchart of this final step of the research is presented. This evaluation is important in order to understand the results of the diagnostic campaigns in the definition of reliable vulnerability assessments and consequent strengthening interventions. In engineering practice, the costs of these tests discourage extensive diagnostic applications. Especially for masonry constructions, where ranges of mechanical values are available in the codes, technicians often limit the diagnostic campaigns in un-

understanding the structural features of the buildings, adopting the mechanical parameters according to MIT2019 [14]. In this work, the comparisons are both made according to three steps: evaluation of the scatter in terms of seismic verifications given by achieving lower KLs; evaluation of potential strengthening interventions compatible with lower KLs; and evaluations of the proposed interventions for KL3 assuming the achievement of lower KLs.

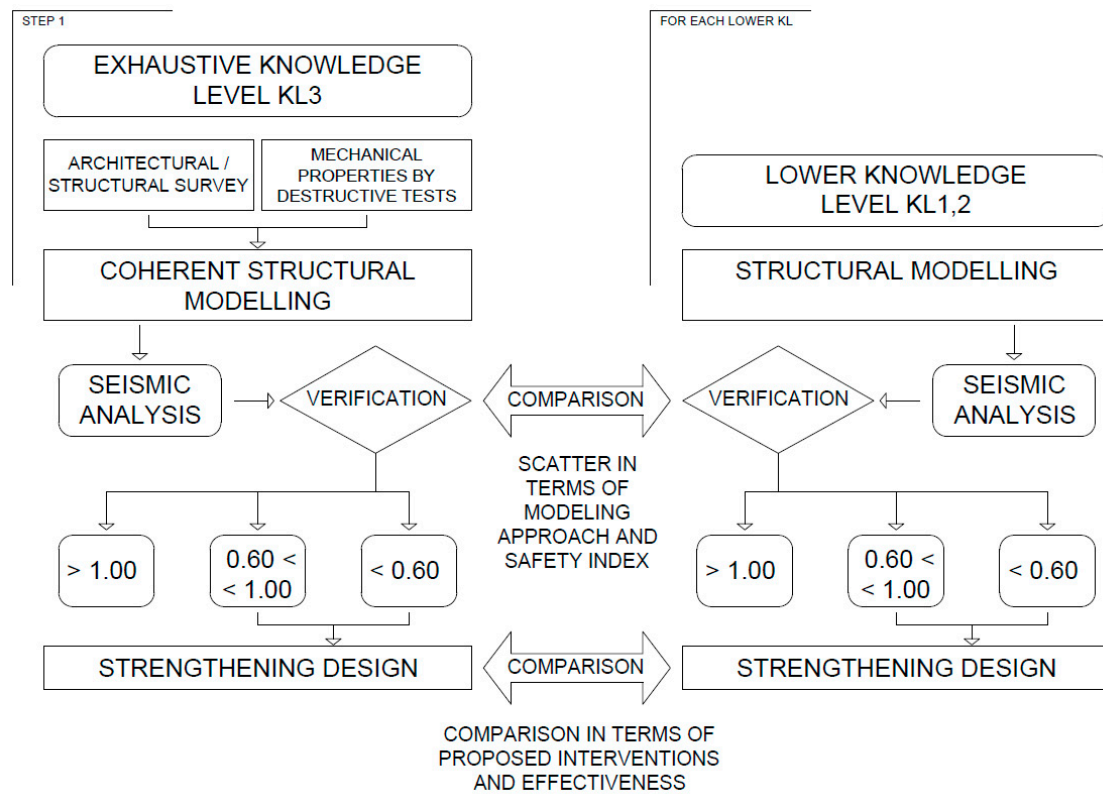


Figure 9. Workflow of the research targeted at assessing the safety indexes and the strengthening solutions based on the achieved KL.

Concerning KL1, the features listed in Table 4 would have been considered. Given the characteristics of the building, depending on the professional sensitivity of each technician, the following analyses could have been applied:

Table 4. Diagnostic investigations and structural assumptions for KL1.

Knowledge Level 1		KL1
Architectural survey	Complete	Laser scanning survey
Structural characterization	Complete	Thermography campaign GPR survey Trial holes + endoscopy
Mechanical properties	Table C8.5.I	Elastic moduli – mean values Resistances – min values
Confidence Factor	CF1	1.35

Kinematic analysis of the upper level of the structure;

Global analysis of the building assuming a limited or null stiffness at the last level.

According to both approaches, the following results would have been obtained depending on the structural investigations carried out.

In the case of assessment of the structural capacity of the building through a kinematic approach, evaluating the overturning capacity of the upper part of the building, this

would have led to the same safety index as the one obtained after the completed cognitive procedure. Values close to the ones obtained in the KL3 model are obtained for the global pushover analyses of the model, where a value of 0.498 is obtained against the 0.445 for KL3. Nonetheless, considering the single walls, KL1 overestimates the capacity of the worst masonry wall leading to a safety index of 0.444. This indicates a scatter of around 0.20/1.00 (+80%), bringing non-conservative results.

In order to achieve the second level of knowledge (KL2), it is generally acknowledged that in masonry buildings the investigation of the mortar properties is sufficient to reduce the confident factors to be adopted. Given the characteristics of the mortar, the issues pointed out achieving the more detailed KL3 would be presented even for KL2. Hence, the two alternative numerical investigations already presented in Section 2.3 could be proposed, in order to dually consider alternate seismic behaviors besides the crumbling effects. For the achievement of the second cognitive level, the information shown in Table 5 would be adopted.

Table 5. Diagnostic investigations and structural assumptions for KL2.

Knowledge Level 2		KL2
Mortar characterization	Accurate	Mineralogic + petrographic analysis Drilling tests
Mechanical properties	Table C8.5.I	Elastic moduli – mean values Resistances – mean values
Detrimental coefficients	MIT2019	Elastic moduli – 0.80 Resistances – 0.70
Confidence Factor	CF2	1.20

For KL2, the safety indexes obtained for SLV according to kinematic assessment, global pushover analysis in X and Y directions and single wall pushover curves are: 0.19, 0.85, 0.46, and 0.42, respectively. In Figure 10, the results in terms of safety indexes for the current configuration of the building are shown with respect of the two presented knowledge levels, KL1 and KL2. It is worth noting that for the kinematic assessment, KL3, as it does not reduce the accelerations for the CF, leads to the highest indexes. On the other hand, the increase of knowledge follows a trend where the lower the knowledge is, the more the analyses tend to overestimate the capacity of the structure. This is particularly evident for the pushover analysis of the single wall, where accounting for KL2 and KL1 brings an overestimation of the structural capacities of 71 and 79%, respectively. On the other hand, for global analyses, the CFs slightly compensate the poor mechanical properties of the building, with overestimation on the order of 11–13%.

3.2. Evaluation of Compatible Strengthening Interventions Based on the KLs

The achievement of each KL is finally discussed both in terms of strengthening design and in terms of obtained safety indexes.

KL1. Considering the strengthening interventions, different solutions could be proposed on the basis of the obtained results. Referring to the kinematic analysis, given the fragility of the Perret ceiling, the proposal of a light and rigid ceiling reconnecting the structure would still represent the most suitable solution, providing an improvement to all the emerged problems of the building (Solution 1).

On the other hand, accounting for the global behavior of the structure in KL1 would also lead to considering a reinforcement of the masonry walls. In addition to the mortar injections, the application of CRM could still be a proposal for strengthening improvements (Solution 2).

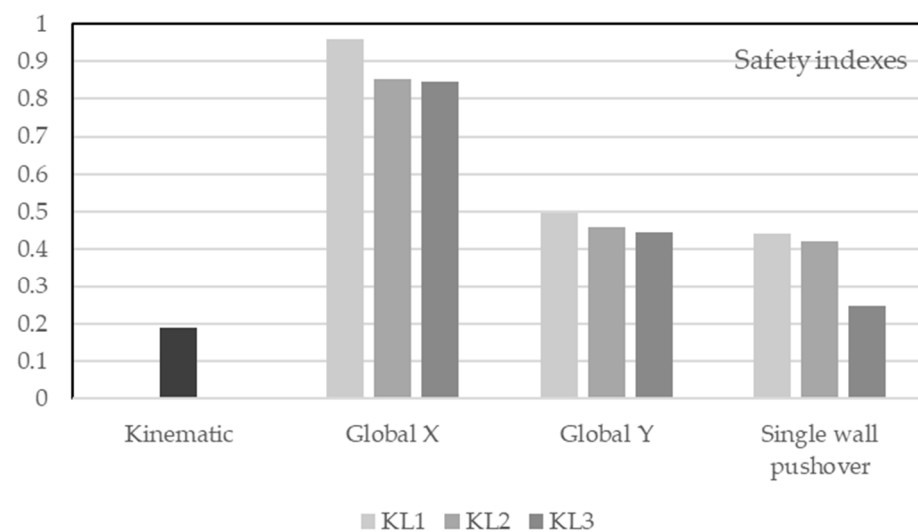


Figure 10. Comparison in terms of safety indexes between the results obtained according to the different KLs. For the kinematic assessment, only one value is obtained since the same CF is adopted regardless the KL [14].

KL2. Due to the poor characteristics of the mortar, the parameters used would have to employ the mean values of the MIT ranges, also considering the detrimental coefficients given by the code (Table 5). Given the characteristics of the building, the proposed interventions could have been the same as proposed for KL3.

On the basis of the above considerations, two distinct cases are assessed:

- (i) The less invasive strengthening solution for KL1 (Solution 1) is evaluated on both the KL1 and KL3 model, in order to understand the real effectiveness of the building;
- (ii) The intervention proposed for KL3 is also executed on the KL1 and KL2 models in order to understand how lower KLs could influence the results.

Concerning the first point, Solution 1 has been tested on the two structural models (KL1 and KL3 models). KL1 leads to a minimum safety index value equal to 0.591 against the 0.463 obtained with KL3. Even with the CF detrimental coefficients, adoption of the KL1 model overestimates the results by around 27%. Observing the indexes obtained for KL1 and KL3, the proposed solution would point out a limited increase of the global capacity; the local mechanisms would be prevented, but this would involve the global capacity of the system, which is not adequate in absence of further interventions. It is worth noting that anything could have been done regarding the mortar quality, since this aspect would not have been investigated.

Concerning point (ii) in Figure 11, a comparison in terms of obtained indexes for the proposed strengthening interventions is shown. Evaluating the interventions proposed in Section 3 for lower KLs, the obtained indexes would increase up to 13 and 15% for KL2 and KL1, respectively. These results are given by the fact that the mechanical values coming from [MIT2019] are assumed, without the Bayesian update through the experimental results. Although the higher detrimental index, the results for KL1 are slightly higher than for KL2, which can be justified by a different distribution of the stress inside the building during the pushover analysis of both models. For the specific case in the case study, as all the indexes are between 0.60 and 1.00, this aspect does not significantly alter the outcomes on the structures. However, in other cases, it could be an important discriminant in the quantification of the strengthening interventions.

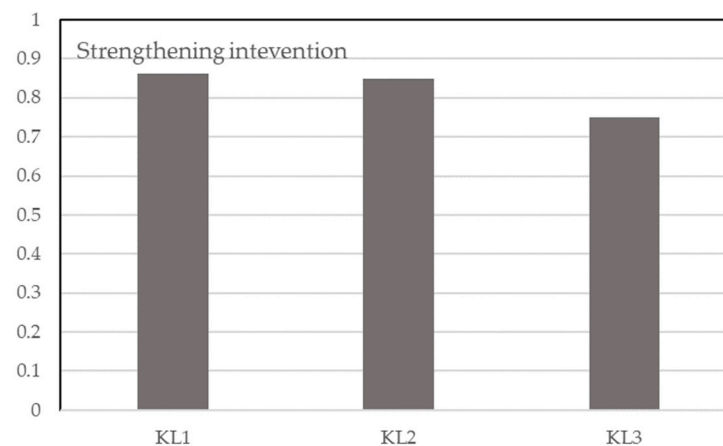


Figure 11. Comparison in terms of safety indexes for the proposed strengthening interventions based on the different KLs.

4. Conclusions

In this paper, a knowledge procedure based on different knowledge levels has been presented with respect to a modern masonry building located in Tuscany. The calibration of reliable structural models is crucial in determining the seismic vulnerability assessment of the existing buildings, and recent technological advances in diagnostic acquisition may lead to the most suitable solutions.

This contribution took advantage of a modern masonry structure used as a nursing home for elderly persons in order to investigate the effects of achieving different knowledge levels for investigation of the seismic performance. The outcomes of the work indicate that acquisition of accurate structural investigations of the current state is the aspect leading to suitable strengthening interventions. A series of outcomes from the research are following:

- For KL1, the research shows that for the considered case study, this KL does not allow an unequivocal characterization of the structure, hence, the determination of the seismic performance of the structure is oriented by the sensibility of technicians, leading to potential overestimation of the structural capacity;
- Concerning the proposal of strengthening interventions, KL1 may lead to the proposal of ineffective solutions which do not consider the poor mortar qualities pointed out by further in situ investigations;
- The mortar investigation (and the consequent achievement of KL2) provides important information that can be the discriminant for reliable analyses;
- Differently than for KL1, KL2 would drive towards suitable strengthening solutions, with an overestimation of the improvements given by the interventions acceptable (15%). A more critical aspect concerns the seismic verifications of the current state of the building, where, based on the poor mechanical values of the case study, the achievement of lower KLs lead to a maximum overestimation of the capacity of the single walls of around 80%;
- Based on the bad performances of the mortar, increased knowledge acquisition does not correspond to an increase in seismic performance, since the effects of the confidence factors is mitigated by the poor mechanical properties of the masonry typologies.

The research is part of a more probabilistic framework targeted at critically analyzing the proposed confidence factors available in the codes. Further and more comprehensive studies will follow, targeted at investigating other existing structures as metamodels representative of wider building classes. These contributions will be focus on analyzing: (i) the effects of these variabilities on different case studies characterized by different dimensions; (ii) the proposal of compatible interventions based on the variability of the previous points. In addition, further investigations will concern the involvement of the cost of the retrofitting solutions, in order to assess the economic impact of different solutions.

The determination of accurate structural and mechanical characterization of the investigated buildings plays an important role in the determination and quantification of the strengthening designs, where the achievement of higher KL can increase the effect of the interventions in the computation of the effective improvement of the performances.

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