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A Framework and Tool for Knowledge-Based Seismic Risk Assessment of School Buildings: SLaMA-School

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Abstract: When dealing with seismic risk assessment at a large scale, the collection of relevant building data is still deemed a challenging task, often leading to limited building knowledge and, consequently, high uncertainties. Therefore, innovative yet standardized frameworks and adaptive tools are needed to support the seismic risk assessment of buildings. Towards this goal, this paper proposes a simplified multi-knowledge seismic assessment methodology involving the analytical-mechanical SLaMA (Simple Lateral Mechanism Analysis) method. An ad-hoc data collection form is first developed to identify the building vulnerabilities by merging and building on existing institutional forms at the international level and integrating new input data. The data are then used to implement the SLaMA-based methodology, at different building knowledge levels, to assess the seismic safety and the economic losses of buildings. The proposed data structure and approach is planned to be included in the "Seismic-Response" module for PELL (Public Energy Living Lab)-School platform, aiming to become a standardized and interoperable database for relevant data of Italian schools and a dashboard for allowing stakeholders to continuously monitor their energetic and static/seismic conditions. The paper discusses the potential and effectiveness of the proposed procedure for large-scale applications and its integration into platforms assessing the energy efficiency of buildings.

Keywords: school buildings; seismic vulnerability; seismic risk; interoperability; data management

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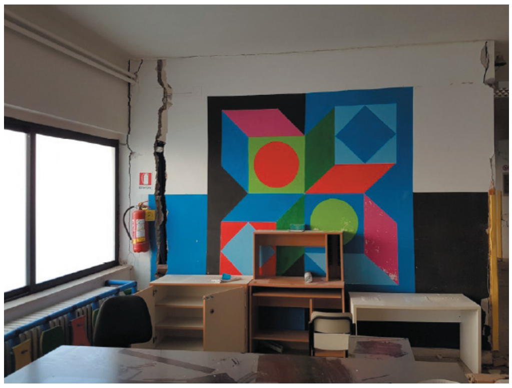
1. Introduction

The severe impact of recent earthquakes in Italy (2009 L'Aquila, 2012 Emilia, 2016 Central Italy) have confirmed the potentially high seismic vulnerability of school buildings (Figure 1). According to the National School Building Registry System (SNAES), the portfolio of Italian schools includes 40.160 actively operating buildings belonging to local authorities, out of which: 43% are located in high seismicity zones; about 70% are designed according to older (pre-seismic) code provisions; 47.6% do not hold a static safety certificate; and 42.1% do not hold the certificate of viability/habitability [1]. Despite the initiatives taken by the Italian Government, including funding for interventions and seismic checks, the situation is critical, and a step-change is urgently needed towards the implementation of seismic risk reduction strategies at national scale through the introduction of either mandatory enforcements (e.g., as in New Zealand [2,3]) or financial incentives (e.g., as in Italy [4]). The urgency of a medium-long-term plan, involving the vulnerability and risk assessment of school buildings, in terms of structural safety and economic losses, as well as the definition of effective and appropriate retrofitting solutions, is more than evident. However, in addition to a higher technical complexity when compared to the design of new structures, the constraint of economic resources and the lack of a prioritization plan at national scale often represent primary obstacles to the practical implementation of such projects [3]. Standardized tools and enhanced procedures are therefore needed for the "diagnosis" and "prognosis" of the seismic vulnerability and expected performance of existing structures, both in terms of safety and socio-economic consequences/losses [5,6].

(**a**)



(**b**)

(**c**)

(**d**)

Figure 1. Damage to school buildings after 2009 L'Aquila earthquake: (**a**) diagonal and (**b**) vertical cracks in masonry infill panels; (**c**) collapse of internal partitions and damage to stairs; (**d**) damage to non-structural and heater elements (Di Ludovico et al. [7]).

To assess the earthquake-prone status of buildings, relevant building data (such as geometry, materials, and structural details) should be first collected and collated in order to identify key vulnerabilities. Following this goal, the Italian Ministry of the Instruction (MI) is digitalizing the data of school buildings throughout the national territory in order to establish a centralized database associated with the Regional Registry of School Building (ARES, "Anagrafe Regionale Edilizia Scolastica"). ENEA is contributing to this process by building an interoperable database within the PELL, Public Energy Living Lab, platform, developed to support the Public Administrations in the definition and implementation of interventions on public buildings, aiming at both their seismic safety and energy management efficiency [8].

The information collected can be processed and used within assessment methodologies —analytical rather than numerical—to identify the structural weaknesses and the seismic risk of school buildings, as well as to guide the selection of retrofit strategies through a cost–benefit approach. Particularly, the SLaMA methodology, acronym for "Simple Lateral Mechanism Analysis" [3,9], could be used as an effective tool for the implementation of national risk reduction plans. The SLaMA is an analytical-mechanical procedure developed "by hand" or using a spreadsheet, rather than, and prior to, a numerical computer-based modeling or more sophisticated analyses [3]. This assessment procedure allows one to evaluate the capacities of the structural members, the hierarchy of strength within each subassembly, and evaluate the overall building system capacity curve and performance levels under different earthquake intensities. The SLaMA provides particularly satisfactory results when considering the simplicity of the method. This analytical procedure can therefore represent an effective tool when different levels of building knowledge are involved. Finally, the SLaMA method results can be used to assess either a Safety Index (IS-V, as defined in Italy [4], or %NBS, New Building Standard, as adopted in New Zealand [9]), as well as an Economic Index such as the Expected Annual Loss (EAL or PAM, "Perdita Annua Media", in Italian), according to the state-of-the-art methodologies for non-linear static analyses. The latter are based on a Capacity vs. Demand comparison in the Acceleration Displacement Response Spectrum (ADRS), i.e., the Capacity Spectrum Method [10], or the N2 method [11]).

It is acknowledged that past research works have investigated the use of simplified analytical methodologies for the seismic vulnerability assessment at territorial scale. For instance, Lagomarsino and Giovinazzi [12] proposed a mechanical method to directly evaluate the capacity curve of an equivalent nonlinear Single-Degree-of-Freedom (SDoF) system, described by three parameters (hardening and softening behaviors are neglected): the yielding acceleration a_y, the fundamental period T_1, and the structural ductility capacity μ. Two different definitions of the capacity curves were proposed for Reinforcement Concrete (RC) and masonry typologies. Focusing on RC frame buildings, Cosenza et al. [13] suggested a mechanically based method by assuming pre-defined collapse mechanisms; for each considered mechanism, the base shear is evaluated by equilibrium relationships, while the ultimate displacement is assessed considering the minimum ultimate rotation of the structural elements. The POST (PushOver on Shear Type models) method, developed by Del Gaudio et al. [14], is based on nonlinear static (pushover) analysis performed on a simplified shear-type structural model and accounting for the influence of infills on the structural response. Moreover, displacement-based methodologies have been proposed in the past decades, such as the DBELA (Displacement-Based Earthquake Loss Assessment) method [15,16] and the SP-BELA (Simplified Pushover-Based Earthquake Loss Assessment) method [17]. In the former method (i.e., DBELA method) the displacement capacity of the structure is evaluated considering an a priori soft-story or a beam-sidesway failure mechanism. The latter (i.e., SP-BELA method) is based on the definition of a pushover curve using a simplified mechanical procedure (similar to the one proposed by Cosenza et al. [13]) and uses a displacement-based framework similar to the DBELA method. The collapse failure mechanism (beam-sway or column-sway) is assessed considering the collapse multiplier λ_i, at each story, as a function of the flexural capacity of the beams and the shear and flexural capacity of the columns. It is worth noting that, typically, the simplified methodologies for seismic vulnerability assessment available in literature are based on failure mechanisms defined "a priori", while the SLaMA method allows one to assess the expected inelastic mechanism through the evaluation of the hierarchy of strength within each beam/column/joint subassembly. Moreover, the joint failures (critical structural weakness affecting the existing RC frame structures [18]) are often neglected in the other available simplified methodologies, since only beam-sway and column-sway (i.e., soft story) mechanisms are taken into account.

This paper presents the work and ongoing research carried out to develop the "Seismic-Response" module of the PELL-School platform (hereafter referred to as PELL-School-RS), aiming to become a standardized and interoperable database for the collection of relevant data for the seismic vulnerability assessment and monitoring of Italian schools ([8,19]). Referring to and building on the data structure of existing official forms defined by the Italian Presidency of the Council of Ministers (PdCM), Department of Civil Protection, with integrations from the forms prepared by the New Zealand Ministry of Business Innovation and Employment [2], the data collection is improved by accounting for additional inputs needed to properly identify the critical vulnerabilities and estimate both the seismic risk class and the expected average annual loss of school buildings, before and after seismic retrofitting interventions.

Considering that the quality of data collected, i.e., the level of knowledge achievable for each school, influences the reliability of the assessment, a SLaMA-based multi-knowledge seismic assessment procedure is herein proposed. The aim is to develop an effective and supporting tool for the rapid estimation of the seismic safety and the socio-economic consequences of buildings, based on the quality and quantities of data collected through the proposed assessment forms and following an adapting and updating process. Therefore, the final output of the procedure consists of a progressive refinement of a range/domain of risk classes and expected vulnerability values (both in terms of Safety Index and Expected Annual Losses) of the school building depending on the data acquisition (knowledge) levels. In line with the Italian regulation (i.e., [4]), the adopted seismic risk classes (form A+ to G) are analogous to the ones used for energy classification of buildings, suggesting a natural and possible integration of the proposed approach into platforms for monitoring the energy efficiency and sustainability of buildings, such as the PELL platform.

It is worth noting that a similar framework for the seismic-capacity assessment of classes of buildings, explicitly accounting for the knowledge level of the built environment, is available in Cosenza et al. [13]. In this methodology, archetype buildings (representative of building classes) are defined by applying a "simulated design" according to the construction practice of the time and as a function of input parameters. The input variables are classified according to their availability: *low order* parameters, easily collected by a rapid external survey (e.g., plan dimension, height, number of stories); *medium order* parameters, that can be collected by inside inspection (e.g., number and length of bays, number of moment-resisting frames); and *high order*, that requires in situ tests (e.g., mechanical material properties). By an illustrative application, the authors showed that, as expected, when a high knowledge level is considered, it is possible to reduce uncertainties in model parameters, therefore reducing dispersion in the results (i.e., base shear coefficient and interstory drift). Although the concept is quite similar, key novelties are introduced in the proposed SLaMA-based multi-knowledge assessment methodologies. Firstly, the procedure is not limited to the definition of archetype buildings but can be applied to existing school buildings (by using data collected through an ad-hoc vulnerability survey form) in order to provide a preliminary seismic-risk classification based on the available building knowledge. In this way, an adaptive and updatable seismic assessment of buildings can be performed, accounting for different data acquisition levels. Thus, information on reinforcement details is explicitly accounted for in the procedure, and a "simulated design" is only needed in case of limited data collection. Moreover, the proposed procedure allows evaluating the seismic risk class of the analyzed structure (even in case of limited building knowledge), returning more useful results for the decision-making process regarding the implementation of further detailed inspection and/or retrofit interventions.

The paper is structured as follows: a description of the proposed ad-hoc data form, as well as of the adopted assessment methodology is provided in Section 2; in Section 3, results are illustrated concerning: (a) a general description of the PELL project and the PELL platform, where the proposed data structure and assessment methodology are planned to be implemented; (b) the proposed framework for multi-knowledge seismic risk assessment, together with an illustrative application on a case-study school building; (c) further applications of the proposed method for school building portfolio at regional and/or national level; finally, conclusions are given in Section 4.

2. Material and Methods

2.1. Proposed Data Structure for Seismic Risk Assessment

When dealing with seismic risk assessment, a fundamental step is the identification and qualitative assessment of any aspect/weakness of the structure that could potentially reduce the seismic performance of the building and, consequently, increase the life safety risk to occupants and passersby and/or lead to negative effects on adjacent neighboring buildings and their activities (inter-vulnerability). Therefore, in addition to the information generally available through existing institutional forms/database, newly defined input data are proposed in order to collect information about crucial aspects to quantitatively assess the building structural capacity and seismic performance. The goal is to collect relevant building data and key vulnerabilities without or prior to performing an extensive and time-consuming numerical analysis. The proposed additional input data can thus be easily collected by engineers from available documentation, in situ testing and inspections, photographic records, and existing reports.

In order to propose an ad-hoc data structure supporting a multi-knowledge seismic assessment of buildings, the information on the source of the collected data and the available documentation is included in the form. This is deemed necessary to explicitly take into account the quality and reliability of the collected data and, consequently, the related uncertainties. Specifically, the compiler can report if relevant building data (and key vulnerability) are collected through expert opinion, interviews, and/or in situ inspections. Information on available material (i.e., structural and/or architectural drawings, historical design documentations, digital drawings, photographic records, and technical reports) is also included in the form.

The additional input data are identified according to the state-of-the-art of seismic assessment procedures at international level. Among others, in the New Zealand guidelines *The Seismic Assessment of Existing Building* [9], particular attention is given to the Initial Seismic Assessment (ISA), considered the recommended first step in the overall seismic assessment process, and to the Initial Evaluation Procedure (IEP), which is an integral part of the ISA process. The IEP is a pre-defined spreadsheet-based assessment procedure returning a preliminary evaluation of the %NBS (i.e., Capacity/Demand ratio at Life Safety limit state). The (desktop-based) IEP procedure requires key input parameters for both seismic demand (i.e., location/seismic zone, soil type) and building data (e.g., building height, construction material, structural system in both orthogonal directions, construction period). The seismic Capacity is thus evaluated by deriving the "design" base shear of the building through an equivalent static procedure, according to the code provisions at the time and using the basic hypothesis/steps that the design engineer would have adopted (e.g., fundamental period, seismic reduction factor). The initial reference value of %NBS in each building direction is obtained by dividing the Capacity by the Demand in terms of spectral ordinate. Finally, this baseline value of %NBS is reduced through suitable reduction factors, accounting for the presence of any critical structural weaknesses and depending on the level of severity. As an example, Figure 2 shows an extract of the code-based spreadsheet used in common practice for implementing the IEP according to the New Zealand guidelines.

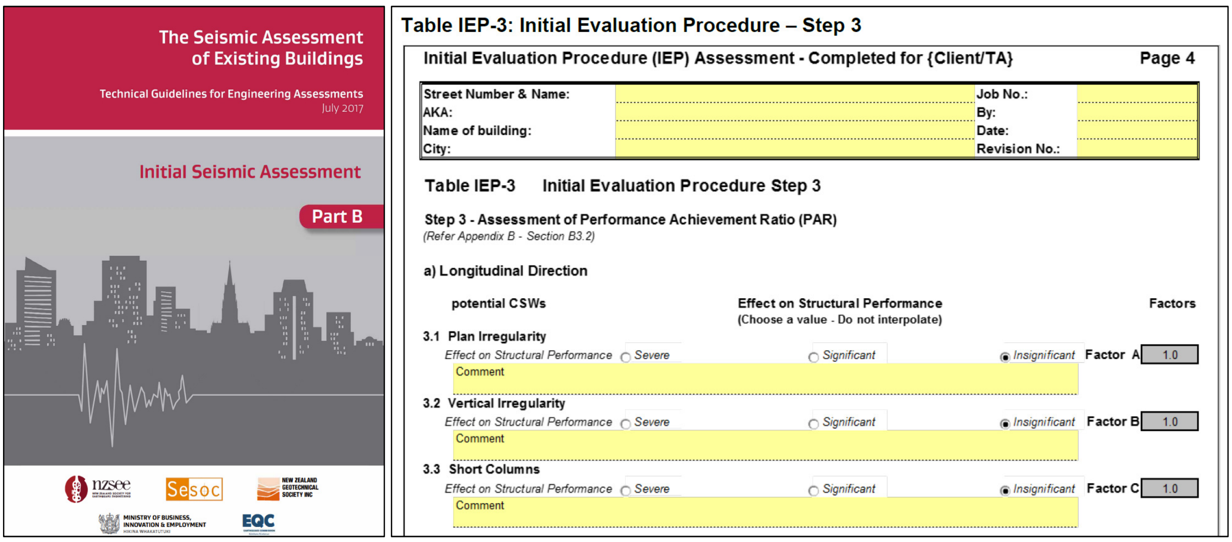


Figure 2. Initial Seismic Assessment (ISA) of existing buildings: front page of the guidelines and extract of the spreadsheet for the Initial Evaluation Procedure (IEP) [9].

In addition to the data available from existing forms, such as the general information on the building position (i.e., isolated, internal, edge) and type of structural system resisting to lateral loads (i.e., frame, wall, and/or both; available from *ARES database* and *PdCM Level 1–2 Form* [20]), newly input data on critical structural weaknesses are included in the proposed data structure. Specifically, these structural weaknesses can be grouped into:

- Geometric criticalities;
- Constructive and material-related criticalities;
- Structural details criticalities.

A brief explanation of the newly proposed data is provided below, focusing on Reinforced Concrete (RC) buildings. It is worth noting that, in line with the IEP procedure, the proposed data structure also includes information on the severity (low, medium, and high severity) of the critical structural weaknesses, CSW, by selecting within a pre-defined multiple-choice menu.

2.1.1. Geometric Criticalities

Geometric criticalities refer to the possible presence of both plan and vertical irregularities.

Data related to plan irregularities include non-symmetrical plan shapes (e.g., L-, T-, E-shape) and/or non-symmetrical structural systems; large spacing of the lateral-resisting systems in case of long-narrow buildings; non-uniform and eccentric distribution of weights; eccentric distribution of stairs and lift shaft; the presence of torsional effects in case of corner buildings. Vertical irregularities refer to the possible presence of: soft-stories; vertical discontinuity of structural systems; transfer beams; vertical lateral-stiffness variation; vertical mass variation. A schematic illustration of plan and vertical irregularities is reported in Figures 3 and 4, respectively. Moreover, geometric weaknesses might also include the presence and dimensions of structural gaps (building separation), which can lead to pounding effects.

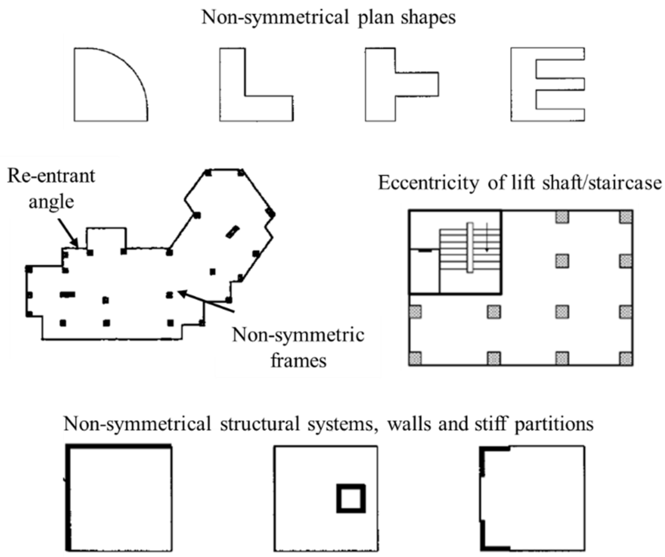


Figure 3. Geometric criticalities: examples of plan irregularities (from NZSEE 2017 [9] and Baggio et al. [21]).

2.1.2. Constructive and Material-Related Criticalities

Constructive criticalities are mainly related to the plan and vertical distribution of infill walls. During an earthquake, infills and surrounding frames have a strong interaction, possibly contributing, on one hand, to the (initial) increase in the lateral strength and stiffness when compared to bare frames. However, on the other hand, the infill–frame seismic interaction can lead to local shear failures of structural elements or global failure mechanisms (e.g., soft-story mechanism, Figure 5a), as pointed out in Magenes and Pampanin [22]. Constructive criticalities also include the presence of short columns (Figure 5b) and the absence of measures able to mitigate brittle collapse mechanisms and out-of-plane expulsions.

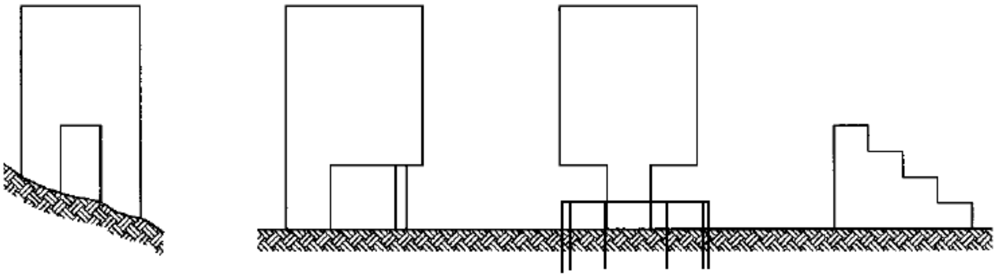
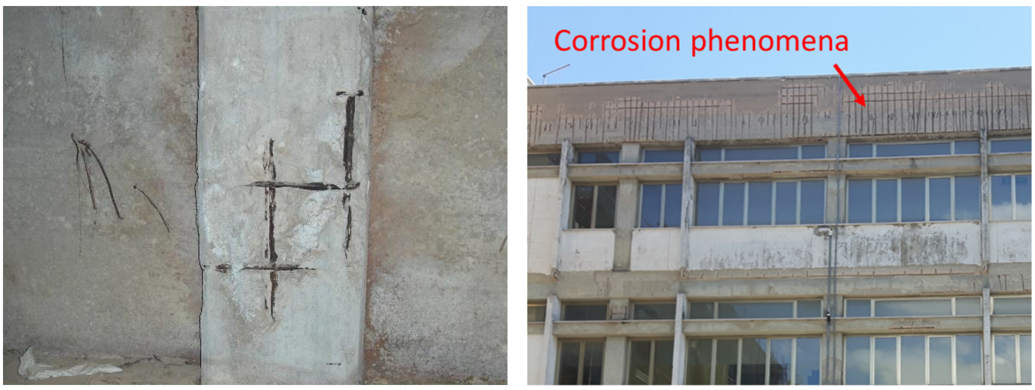


Figure 4. Geometric criticalities: examples of vertical irregularities (from [9]).

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

Figure 5. Construction criticalities: example of (**a**) non-uniform vertical distribution of infill walls, possibly leading to a soft-story failure mechanism, and (**b**) brittle failure due to short columns.

Material-related criticalities for RC buildings mainly refer to: low-quality concrete (e.g., low values of compression strength); degraded concrete; low-quality steel bars; use of plain round bars; and presence of corrosion phenomena. Poor materials and deterioration might lower, even considerably, the capacity of structural members. An example of degradation and corrosion phenomena observed during in situ surveys is reported in Figure 6.



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

Figure 6. Example of corrosion phenomena to a column in the basement (**a**) and façade structural members (**b**) observed during in situ surveys (from UEFA/ELENA research project [23]).

2.1.3. Structural Detail Criticalities

Structural detail criticalities refer to a general lack of provisions related to the "capacity design" (hierarchy of strength) philosophy, as well as to the presence of not-code-conforming construction details (typically observed in existing buildings).

The form includes information related to the absence of hierarchy of strengths (capacity design) principles at a global building level. This weakness can be identified in presence of strong beams and weak columns (Figure 7), as a consequence of incorrect design methods adopted in the past, based on gravity loading only and not accounting for seismic (lateral) forces.

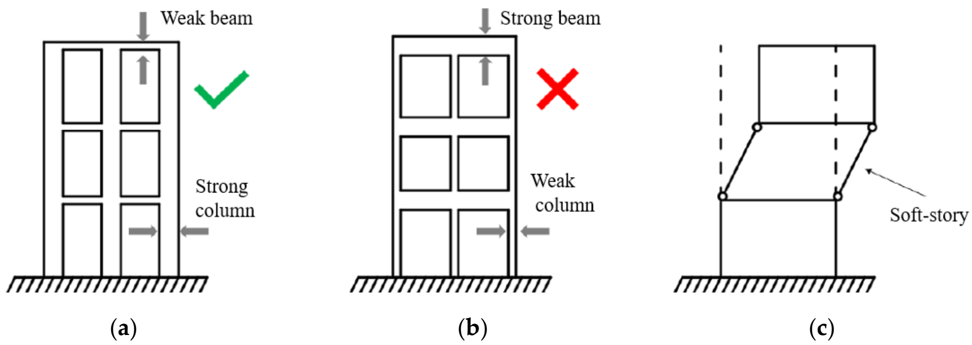


Figure 7. Structural details critical to the seismic response: example of presence (**a**) and lack (**b**) of hierarchy of strengths (capacity design) principles; a lack of hierarchy of strengths principles can lead to a soft-story failure mechanism (**c**).

Structural detail criticalities at the local component level involve: the detailing of beam–column joints; the steel reinforcement ratios; longitudinal and transverse steel spacing and detailing of structural members; the location of lap splices and anchorage of longitudinal bars; and the detailing in the critical dissipative zones.

Moreover, in order to estimate the local and global capacity of the building, further data on local dimensions are also requested. This represents a key novelty of the proposed form when compared to the existing institutional form, allowing one to assess the seismic capacity of the building (both in terms of expected inelastic mechanism and global force-displacement capacity curve) by a simplified analytical-mechanical procedure, as explained in the following section. Specifically, the form includes: the length and number of spans in both structural directions; the section geometry (width, height) and reinforcement quantities (longitudinal, transverse) for beams, columns, walls; the beam–column joint details; the thickness of the floor slab and its reinforcement details.

2.2. Assessment Methodology

The building data collected through the proposed form can be used to develop a seismic risk assessment of the existing structure. This investigation can be rapidly implemented by using analytical assessment procedures, such as the Simple Lateral Analysis Mechanism (SLaMA) method (Figure 8) described in the NZSEE 2017 Seismic Assessment Guidelines [9]. Following this approach, a rapid estimation of the safety level of the buildings as well as of the expected annual losses can be computed, without any need for a numerical model. SLaMA provides satisfactory results when considering the inherent simplicity of the method, as also proved in different analytical–numerical comparisons (e.g., [24–26]). Therefore, it represents an effective tool when different levels of building knowledge are involved. As a matter of fact, vulnerability assessment studies are significantly influenced by the achievable level of building information, adding further uncertainties to an already complex problem. SLaMA can be easily implemented to develop a preliminary evaluation of the probable building capacity, then results can be further improved when additional building data are available.

The SLaMA assessment procedure develops from the identifications of the critical structural weaknesses (CSW) through: (1) the evaluation of the flexural and shear capacity of the structural members (i.e., beams, columns, and beam–column joints); (2) the hierarchy of strength and sequence of events of the connections and beam–column subassemblies (according to Pampanin et al. [27]); and (3) the local and global collapse mechanisms and the building capacity curve.

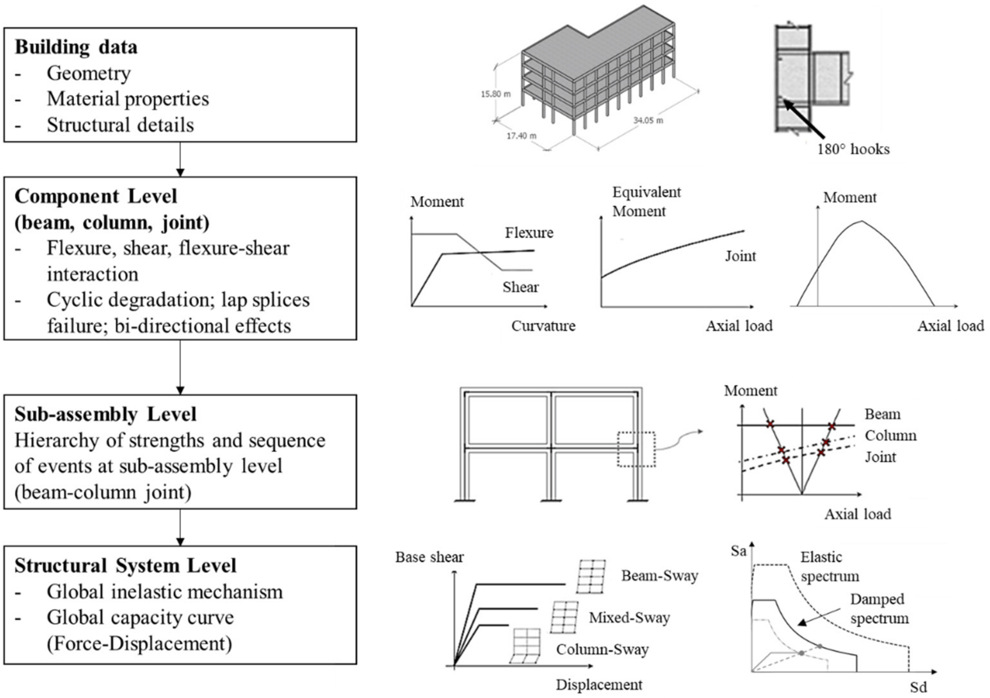
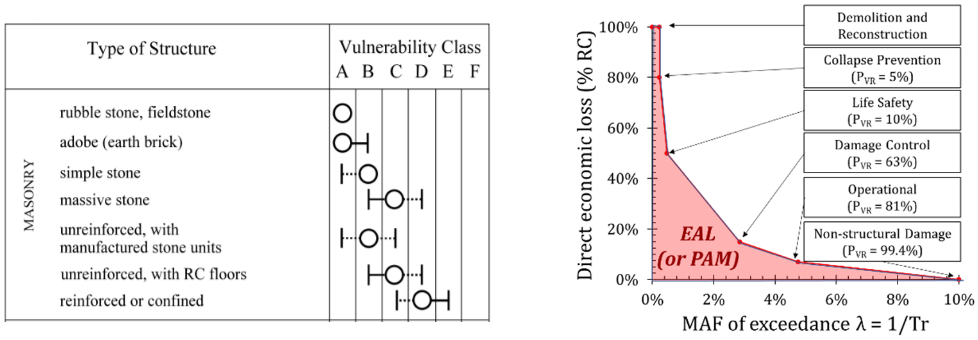


Figure 8. Key steps of the SLaMA assessment procedure according to NZSEE 2017 [9].

Comparing the Capacity curve of the structure (in terms of analytical force–displacement non-linear curve) and the Demand (in terms of ADRS, in line with the Capacity Spectrum Method [10] or N2 method [11]) the seismic performance of the building under different levels of shaking intensity, i.e., earthquake return periods, can be evaluated with a good level of approximation. More specifically, the method allows one to evaluate the level of safety when compared to a newly built structure by means of a capacity–demand ratio, i.e., the %NBS index as per NZSEE 2017 [9] or the Safety Index (IS-V or ζ_E) according to the DM 65 [4], as well as the achievable reduction of the economic losses, evaluated through Expected Annual Losses (EAL) or similar indicators, according to the state-of-the-art methodologies available for non-linear static analysis; the Seismic Risk Class of the existing building can be finally identified. Therefore, the SLaMA approach naturally forms the fundamental first step to assess the seismic risk of existing buildings, define appropriate retrofit strategies, and compare alternative options by considering the overall performance improvement under different earthquake intensity levels.

To support the SLaMA-based risk assessment, in the proposed assessment methodology, the estimation of the safety and economic building indicators adopts the methodology currently applied in Italy for the classification of the seismic risk of residential buildings [4]. The procedure proposes the calculation of a Safety Index (IS-V or ζ_E) of the building which is computed as the Capacity vs. Demand ratio in terms of PGA at Life-Safety (SLV) intensity level (same as the Risk Indicator defined in the PdCM Form). The guidelines, also referred to as "SismaBonus", provide a general framework to identify the Seismic Risk Class of buildings, as well as the rules to access significant financial incentives when implementing—on a volunteering basis—seismic retrofitting interventions. The Risk Class can be assessed through two different approaches: (1) the "simplified" approach, applicable to masonry buildings and based on the qualitative and archetype-based classification provided by the European Macroseismic Scale (EMS-98 [28], Figure 9a; and (2) the "conventional" approach, based on the estimation of the capacity and demand through the implementation of the current code provisions for the estimation of both the Safety Index (IS-V or ζE) and the Expected Annual Losses (EAL, or PAM in the Italian guidelines). The EAL (or PAM) index is evaluated by assessing the seismic performance in terms of Mean Annual Frequency (MAF or $\lambda = 1/T_R$) at different Limit States. Based on the comprehensive database of the cost of repair and reconstruction in the aftermath of the L'Aquila earthquake 2009 ("White Book" [29–31]), a direct economic loss, expressed as a percentage of the Reconstruction Cost of the building (%RC), is associated with each Limit State and the EAL index is defined as the area underneath the λ–RC curve (Figure 9b). Finally, the Seismic Risk Class of the building is defined as the minimum between the two classes associated with the safety and economic indicators (from A+ to F for IS-V, from A+ to G for EAL or PAM, where A+ identifies higher performance).



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

Figure 9. (**a**) Identification of the vulnerability classes for masonry buildings through the simplified approach based on the European Macroseismic Scale EMS-98 [28]; (**b**) EAL or PAM curve as defined in the SismaBonus guidelines [4].

3. Results

This section presents the work and going research developed for the implementation of the proposed SLaMA-based seismic assessment methodology in the "Seismic Response" module of the PELL-School platform. A brief description of the PELL platform is firstly provided, focusing on its interoperability nature and thus its ability to source data from existing institutional forms. In line with the purposes of the PELL project, the data collection is improved by accounting for additional inputs, according to the proposed data structure described in the previous section. Moreover, the section discusses through the implementation on a case study building, the potential of implementing the proposed framework for multi-knowledge seismic risk assessment of individual school buildings, as well as further its possible and natural extension to (school) building portfolio at regional and/or national scale.

3.1. PELL-Platform

In line with the digitization of data and information related to the public administration assets, the PELL (Public Energy Living Lab [32]) project aims to promote and support a more efficient and effective management of energy-intensive infrastructures and strategic structures (e.g., school buildings, hospitals), providing management tools to the stakeholders in order to support an informed decision-making process related to targeted development objectives [19]. To achieve this goal, the development and adoption of new methodological and technological solutions for an automatic and constant assessment—in a uniform and standardized way—of both physical and functional conditions of the structure under analysis is needed.

Therefore, thanks to the financial support of the Italian Minister of Economic Development (MiSE), the PELL platform has been developed in order to:

(a) Achieve a minimum standard of building knowledge;
(b) Allow for interoperability with other existing databases by developing data-transmission protocols;
(c) Monitor and evaluate buildings performances and services;

(d) Enhance seismic safety and energy efficiency of public buildings by supporting the Public Administration (PA) in Italy towards the definition and implementation of integrated rehabilitation interventions.

The vertical PELL platform is a smart city as-a-service platform, characterized by a general framework based on data collection from different infrastructures and managers and the development of tools and services for end-users (Figure 10).

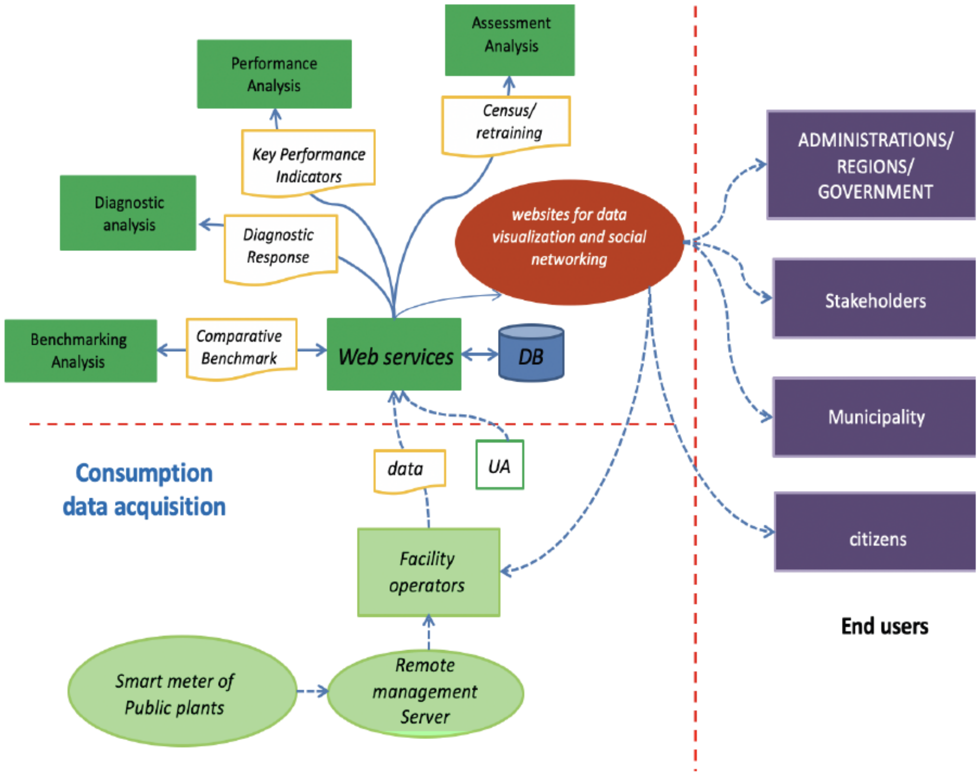


Figure 10. PELL Platform, ICT layout (https://www.pell.enea.it/la-piattaforma, accessed on 5 July 2022).

The PELL platform can operate in a static and a dynamic mode in order to support both the collection of data on structures/infrastructures and the continuous monitoring of the structure/infrastructure performance [8].

In this paper, particular focus is given to the ongoing activities for the development of the "Seismic-Response" module of the PELL-School platform. Through this module, the PELL project aims to provide a standardized and interoperable database for the collection of relevant data on Italian school buildings, involving crucial data for their seismic vulnerability, risk assessment, and monitoring. The goal is to provide a seismic assessment tool, included in the PELL platform, able to return a preliminary seismic risk classification of each school depending on the level of knowledge achievable (i.e., quality and quantities of the information available and collected). Such an approach/tool can support the implementation of a medium-long-term plan of seismic risk reduction at a national scale.

3.1.1. PELL-School-RS

Considering the interoperable nature of the PELL-School platform, the "Seismic-Response" module replicates and builds on the data structure of different official forms and screening approaches available in the Italian regulation and practice: the ARES database, part of the National School Building Registry System; the forms defined by the Italian Presidency of the Council of Ministers (PdCM), Department of Civil Protection, according to ad-hoc technical specifications from the Agency for Digital Italy (AgID [33]); the so-called "SismaBonus" guidelines [4] by the Ministry of Infrastructure and Transport (MIT); and other existing forms, such as the "CLE, Limit Condition in Emergency" [34]. Furthermore, additional input data are proposed and included in the PELL-School-RS module, in order to collect information about crucial aspects to determine the structural capacity (e.g., building geometry, typology of structural systems, etc.) and identify Critical Structural Weaknesses (CSW) that could potentially reduce the building seismic performance. This data can be identified by engineers from available architectural and structural drawings, in situ testing and inspections, photographic records, and technical reports. The data collected can be used to assess the seismic risk of the building, e.g., by implementing the SLaMA method [9], i.e., a simplified analytical-mechanical seismic assessment procedure fully applicable according to the Italian code ([35]) provisions.

Key Performance Indicators (KPIs) are thus included in PELL-School-RS, involving both static KPIs and dynamically computed KPIs. In line with the approach officially adopted in Italy and described in the "Guidelines for the Seismic Risk Classification of Buildings" [4], the static KPIs provide a measure of the seismic vulnerability and risk of buildings, whereas the dynamically assessed KPIs aim to provide a quasi-real time estimation of the earthquake-induced damage to the instrumented buildings.

The final goal of the PELL-School is therefore the collection of data and assessment of KPIs towards a continuous monitoring of the school resilience both in business as usual time and in consideration of possible crisis events. In particular, the dynamically assessed KPIs can support and inform post-disaster operations of damage and usability assessment. As far as seismic events are concerned, the idea is to include in PELL-School-RS data relevant to all the Disaster Risk Management cycle, involving three different phases: before the earthquake (to evaluate the building earthquake-prone status in their as-built configuration), during the event (to assess the post-earthquake safety and usability/operability), and after a disaster (to assess the post-earthquake damage, assess the residual capacity and safety, and plan the repair/reconstruction phases).

3.1.2. Data Sourced from Existing Forms

PELL-School is interoperable with the ARES Database, managed by the Italian Regions whilst being continuously updated by Municipalities, Provinces, and Metropolitan Cities through a graphical user interface. In ARES, data are acquired at both *Building Level* and *Structural Unit* (*US*), and information related to school consistency and functionality is also collected. Sections A to C in ARES include relevant data for seismic vulnerability assessment; thus, they are considered to source data for PELL-School-RS module. Specifically, Section A includes identifier data of the school building. Section B includes identifier data of each *US* and their structural information, i.e., material and typology of the main vertical and horizontal structural systems and particular construction techniques, as well as design code, adopted seismic retrofit interventions, and related risk indicator assessed according to the legislation in force at the time of the design and execution of the work. Section C includes data on the use of the *US*, as well as geometric and dimensional features (e.g., number of stories, floor area); and constructive techniques of non-structural elements; information on maintenance/retrofitting interventions, if any, for both structural and non-structural elements. The data acquisition from these sections is facilitated through a webservice established between ARES and PELL-Schools which allows them to periodically check for and acquire newly uploaded data and/or updated data.

The PELL-School-RS module sources additional data from two institutional assessment forms established by the Ordinance of the Presidency of the Council of Ministers (OPCM) n. 3274 [20], namely: *PdCM Level 0 Form* and *PdCM Level 1–2 Form*. *PdCM Level 0 Form* represents a preliminary screening of the structures supporting a prioritization for their seismic vulnerability assessment and identification of any required seismic retrofit intervention. Several data from *PdCM Level 0 Form* are already included in ARES database, namely: geometric data, construction period, material of the primary vertical structural system, building use, and presence of retrofitting interventions. *PdCM Level 1–2 Form* collects all the information needed to perform an engineering assessment of the building seismic vulnerability, according to the codified methodology in the Italian seismic code [35] assessing a Risk Indicators (α) defined as *US* Capacity vs. Demand ratios. *PdCM Level 1–2 Form* includes several sections where data are collected either as unique or multiple-choice questions, as well as by fill-in boxes, where written or numerical information needs to be provided. Data included in *PdCM Level 1–2 Form* are replicated in PELL-School-RS.

As mentioned above, other existing approaches are taken as a reference to develop the PELL-School-RS module: the so-called "SismaBonus" guidelines [4] and the "CLE, Limit Condition in Emergency" form [29]. Concerning masonry buildings, the "SismaBonus" proposes a "simplified" approach which involves the European Macroseismic Scale EMS-98 [28] typological classification to attribute a typological seismic vulnerability class to the building and provides a list of constructive and geometric criticalities/peculiarities to be surveyed and accounted for when assessing the seismic risk. Following the macroseismic approach proposed by Lagomarsino and Giovinazzi [12], "SismaBonus" establishes that a masonry building can be judged to belong to a seismic vulnerability class based on its typological identification. In addition to several possible criticalities and peculiarities described in the document, the masonry typologies recognized by "SismaBonus" (i.e., the same in EMS-98) are integrated in PELL-School-RS module with the ones considered by the *PdCM Level 1–2 Form* and ARES database. Regarding the "CLE, Limit Condition in Emergency" approach, this comprises five different forms, namely: Strategic Building, ES; Emergency Area, AE; Infrastructure Accessibility/Connection, AC; Structural Aggregate, AS; Structural Unit, US. PELL-School-RS is now including part of the CLE form data structure that collects relevant data on the possible negative interaction between adjacent US due to: the misalignment between roofs, slabs, or façade walls; the misalignment in interior spaces; juxtaposition or structurally poorly connected elements; incongruous punching system; isolated pillars, arcades, and pilotis floors; and the presence of terraces, towers, and chimneys.

As mentioned above, in order to estimate the local and global capacity of the building, as well as the key vulnerabilities possibly affecting the building seismic performance, additional input data are included in the PELL-School-RS form, in line with the proposed data structure reported in Section 2.1. This represents a key novelty of the PELL-School-RS form when compared to existing institutional forms, and it is deemed necessary to quantitatively assess the seismic capacity of the building (both in terms of expected inelastic mechanism and global force–displacement capacity curve).

3.2. Multi-Knowledge Seismic Assessment: Implementation on a Representative/Prototypical Range of Possible Situations

To overcome the issue related to limited building information, a multi-knowledge SLaMA-based seismic assessment procedure is proposed to assess the seismic risk of existing RC schools. By coupling the PELL-School-RS module with the SLaMA method, an adaptive and updatable seismic assessment of buildings can be performed, accounting for different data acquisition (knowledge) levels. More specifically, the PELL-School-RS form includes information about the material and/or documentation available for a building, therefore, the building Knowledge Level (KL) can be defined based on the data collected, as conceptually shown in Figure 11.

Building knowledge can be grouped into three macro-categories, concerning information on (1) geometric details, (2) reinforcement and structural details, and (3) material mechanical properties. Available material and/or documentation can increase the knowledge in one or more macro-categories depending on the quality of information collected, conceptually represented by one-to-three "stars" (from low to medium to high quality information) in Figure 11. As an example, considering the mechanical material properties, code and/or guidelines of construction time provide basic (i.e., low quality) information (e.g., historical code provisions for concrete compressive strength and steel yield strength), while an exhaustive testing campaign on material samplings provide higher quality information. Finally, by collecting the available material and considering the related quality of information, different knowledge levels can be identified.

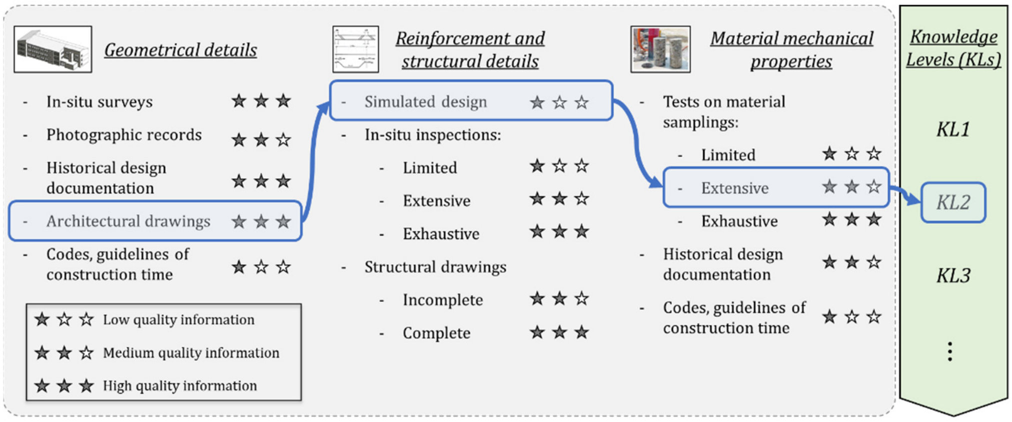


Figure 11. Conceptual identification of different Knowledge Levels (KL) based on available material/documentation.

It is worth mentioning that a similar identification of knowledge levels can be found in the Italian building code (NTC 2018, [35]). In this document, three different *Knowledge Levels* (referred to as LCs, "Livelli di Conoscenza", in Italian, according to the NTC nomenclature) are defined based on the available historical documentation and the exhaustiveness of the in-situ inspections and tests on materials (three different levels of exhaustiveness are defined for both, namely "limited", "extensive", and "exhaustive"). A *Confidence Factor* (FC, "Fattore di Confidenza", in Italian) is thus associated with each LC in order to account for different reliability levels of the data collected. However, it is worth noting that even the lower LC (i.e., LC1) defined in the Italian code requires limited in situ inspections, as well as limited tests on material samplings. On the contrary, knowledge levels identified by the PELL-School-RS form could even refer to scenarios where no in situ inspections and/or tests on material samplings are collected (typical of large-scale applications). In other words, Knowledge Levels KLs, (or "Livello di Conoscenza" in Italian, LCs) of the Italian building code should be considered as the minimum dataset required to perform a code-compliant seismic assessment, while Knowledge Levels (KLs) of the herein proposed procedure refer to the availability and quality of data at the time of seismic assessment, possibly improved in the future, in a dynamic and adaptive way, when more building data become available. Hence, LCs defined in the NTC 2018 could be considered as sub-classes of the "complete" knowledge level defined in this research work. This concept is shown in Figure 12, where different Knowledge Levels (from *KL1*—basic data acquisition—to *KL3*—complete data acquisition) are tentatively defined based on the available material/documentation. It is worth noting that, in Figure 12, geometric details of the building are deemed as always collected, since this information is necessary to perform a seismic assessment of the structure, even when considering a basic data acquisition level.

In Figure 12, the Knowledge Levels defined by NTC 2018 (Livelli di Conoscenza, LCs) are also indicated. It can be noted that, for the proposed procedure, the quality of information required by NTC 2018 is deemed as a *Complete data acquisition (KL3)*, since documentation related to both reinforcement/structural details and material properties are needed. The definition provided by NTC 2018 can then be used to identify different sub-classes of knowledge levels within the *KL3* class. On the other hand, in *Incomplete data acquisition (KL2)* and *Basic data acquisition (KL1)* levels, limited (basic) information is collected in terms of reinforcement/structural details and/or material properties. This is in line with the goals of this research work, aiming to provide a procedure and tool for the seismic assessment of buildings accounting for lack of material and documentation.

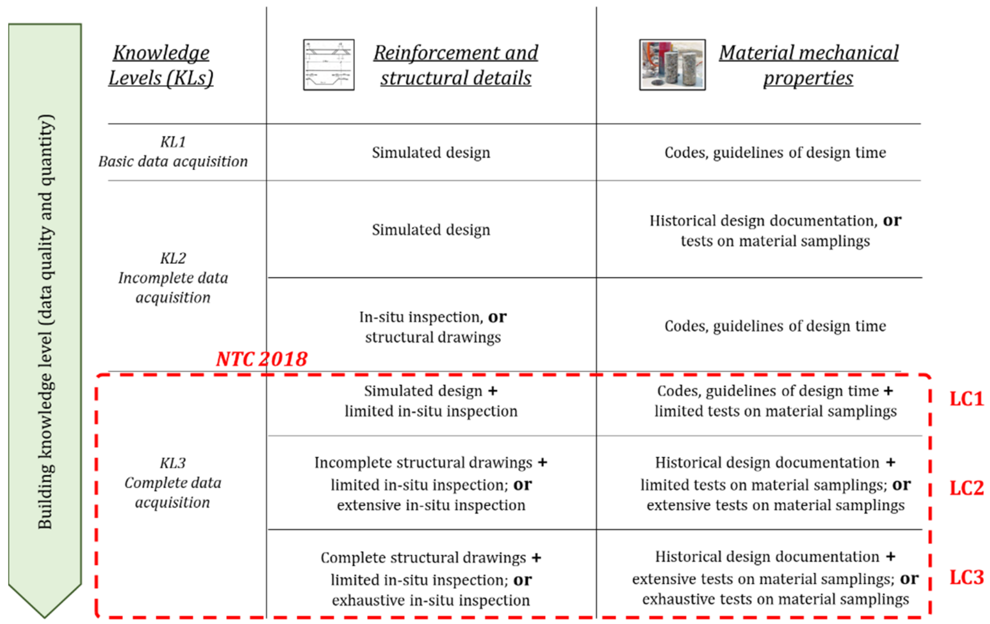


Figure 12. Definition of Knowledge Levels herein adopted based on the available material and documentation and comparison with the Livelli di Conoscenza, LC, from the Italian Regulation, NTC2018 [35].

From an alternative and complementary perspective, different-yet realistic in the common practice-scenarios of data collection can be identified through the PELL-School-RS module. In the proposed procedure, the seismic assessment is influenced by the quality and quantity of the available material. If limited or incomplete information is collected, assumptions are needed according to the construction period of the building and referring to codes and guidelines of that time. Moreover, uncertainties on material properties and/or construction details should be introduced following either deterministic/semi-probabilistic (parametric) or probabilistic (mathematical distributions) approaches. An example of different scenarios of data acquisition is conceptually shown in Figure 13.

As a starting point of the SLaMA-based procedure, information on the construction period and geometric details (i.e., plan dimension, total height, number of stories and bays, inter-story height, bay width, beam/column cross-sections) are required as a minimum dataset. In the absence of additional documentation (i.e., *Scenario 1* in Figure 13), important assumptions (typically on the conservative side) are needed for the identification of material properties and construction details in order to assess the seismic performance of the structure. More specifically, a "simulated" design is required to identify the minimum reinforcement quantities of the structural members. Moreover, assumptions are needed to define material mechanical properties, based on the construction time. Consequently, high uncertainties in the results are expected, yet a preliminary identification of the potential local and global mechanisms can be derived.

Similarly, the distance between "events" within a hierarchy of strength approach, can be appreciated, whilst accounting for the aforementioned high uncertainties, and actually suggest further localized screening tests and/or specific in situ inspections. As an example, in the case of a clear weakness of a beam–column joint, characterized by no stirrups and inadequate construction details, and regardless of the concrete mechanical properties (estimated within a wide range of values, e.g., 10–25 MPa) or of a clear expected soft-story mechanism (given the significant difference between column and beam sizes and/or the presence of a pilotis story, regardless of the type of steel being used), the strategic decision could be to by-pass a comprehensive testing campaign and plan a retrofit intervention to resolve the critical structural weakness, regardless of the KL or LC level achieved.

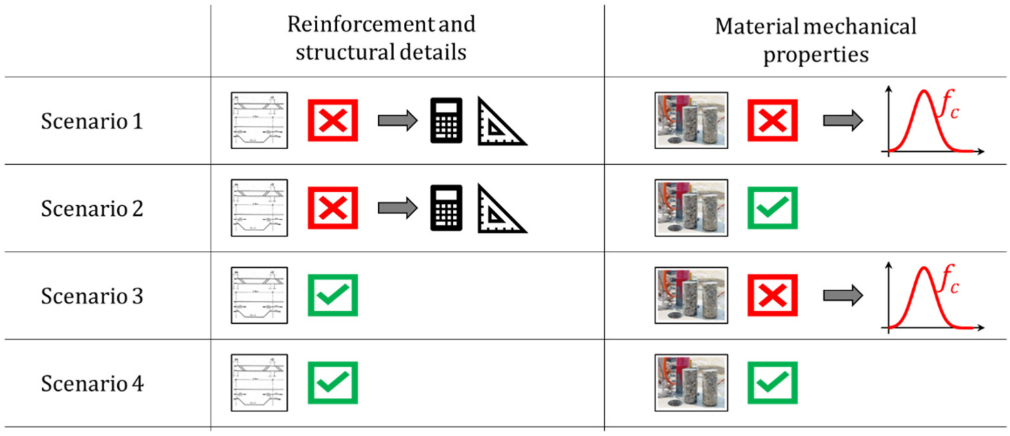


Figure 13. Conceptual illustration of alternative data acquisition scenarios.

Moving to an incomplete data acquisition level (i.e., *Scenario 2* and *Scenario 3* in Figure 13), in addition to the information on geometric details and construction period of the building, information on material properties or reinforcement and structural details is collected. As an example, in *Scenario 2* it is assumed that tests on material samples and/or historical design documentation, including material properties, are available. Therefore, the quality of data on material properties is improved when compared to *Scenario 1*. However, a "simulated" design is still required to identify the minimum reinforcement quantities of the structural members. In this scenario, uncertainties can be introduced in a parametric way by considering different configurations, characterized by different bar diameters and anchorage details, as well as different stirrups diameter and spacing for beams, columns, and walls.

In *Scenario 3*, it is assumed that no information on the material properties is collected, but structural drawings and/or in situ inspections are available. Therefore, assumptions are needed in order to define material mechanical properties according to the construction period. This can be performed considering the most relevant research works available in literature, providing mechanical properties of typical materials used in the past (e.g., [36,37]). An example of identification of different Italian building classes (Pre-1976, 1977–2007, Post-2008), based on past codes (from Regio Decreto 1939 [38] to NTC 2008 [35]) and accounting for the evolution of structural details and material mechanical properties, can be found in Gentile et al. [39]. Uncertainties can be taken into account by sampling a discrete number of values from the probabilistic distribution of compressive strength and yield strength for concrete and steel, respectively (Figure 14).

Finally, *Scenario 4* (in Figure 13) represents the case of complete building knowledge, i.e., all the information required for a code-compliant seismic assessment of buildings is collected. Therefore, it is assumed that structural drawings and/or in situ inspections for reinforcement and construction details and tests on material samplings and/or historical documentation for material mechanical properties are available. As mentioned above, according to the NTC 2018, different LCs can be identified for this scenario based on the exhaustiveness of the data collected.

By implementing the analytical-mechanical SLaMA method, global pushover capacity curves can be obtained for each scenario, as well as the Beam-Sway (upper bound, weak beam/strong column) and the Column-Sway (lower bound, strong beam/weak column) capacity curves. When an incomplete data acquisition level is considered, the multi-knowledge assessment procedure allows identifying a range of possible capacity values/curves without the need for numerical simulations (Figure 15). The range can be further narrowed (until the identification of a single capacity curve) when/if more data on the building should become available.

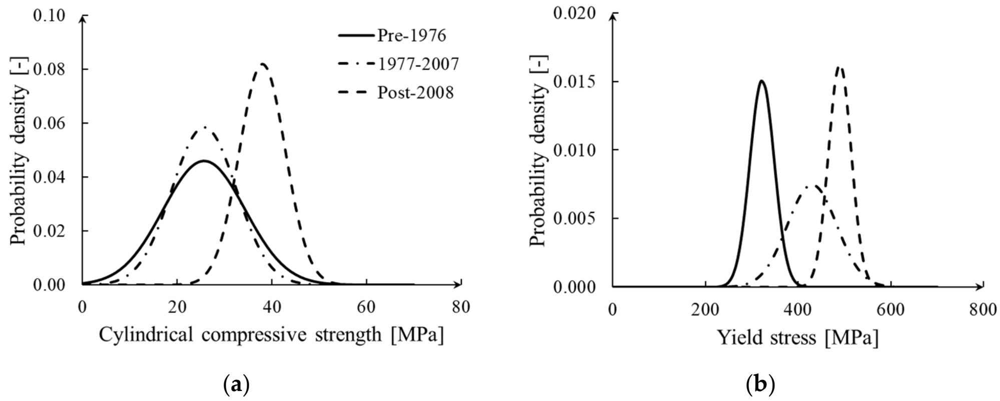


Figure 14. Possible definition of probabilistic distributions for material properties: concrete compressive strength (**a**) and steel yield stress (**b**).

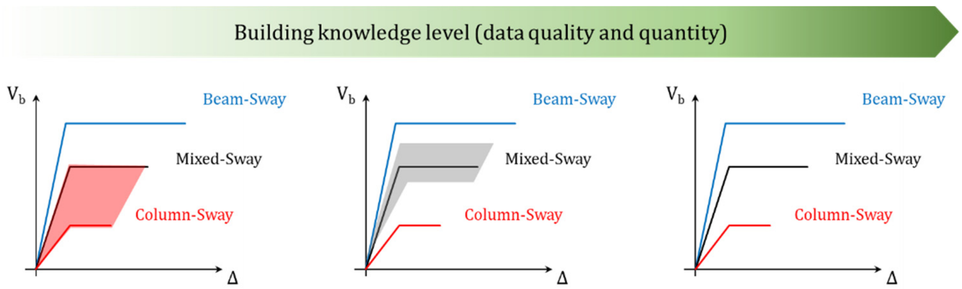
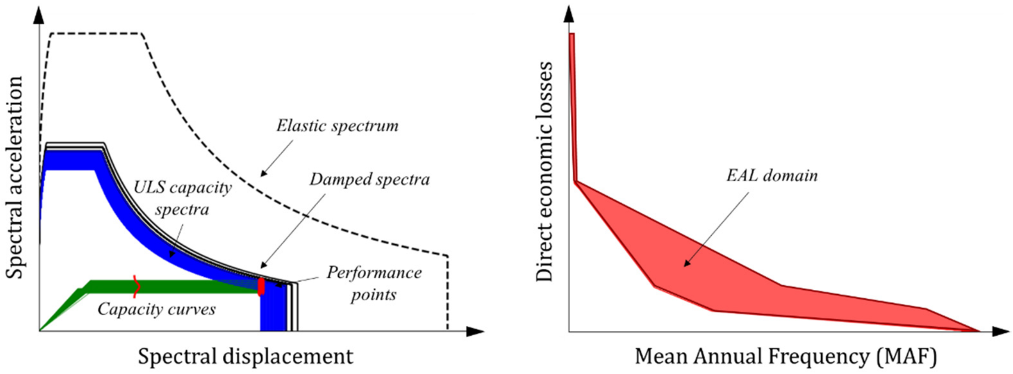


Figure 15. Conceptual illustration of SLaMA pushover capacity curves accounting for different building knowledge level.

As mentioned in the previous section, SLaMA pushover curves can be used to assess the seismic risk class of the building, according to the Italian "SismaBonus" guidelines ([4,40]). The methodology can be implemented by evaluating the Capacity/Demand ratios at different limit states (from Operational to Collapse Prevention) in the ADRS domain, as per Capacity Spectrum Method [10] or similar approaches (e.g., [11]). In case of limited/incomplete data acquisition, the methodology is applied to each parametric capacity curve. This leads to the identification of different performance points (Figure 16a) and, consequently, of a range of IS-V (Capacity vs. Demand ratio) and EAL values (Figure 16b).

By computing the IS-V and EAL indices for all the possible failure mechanisms (Beam-Sway, Mixed-Sway and Column-Sway), the seismic risk class and associated range of values can be evaluated. The final output of the procedure consists of a range/domain of expected (most likely), possible (probable cases), and exceptional (less probable, exceptional cases) values of IS-V and EAL values (similarly to [28]), as conceptually shown in Figure 17.

When the minimum dataset is considered (i.e., *Scenario 1*), the highest dispersion is expected. This is due to a general lack of knowledge, leading to important and conservative assumptions. In this scenario, expected IS-V and EAL values can be considered between the Column-Sway and the Mixed-Sway results. Moving to incomplete data collection (i.e., *Scenario 1* and *Scenario 2*), the domain of the expected index values (both IS-V and EAL) can be identified by considering the minimum and maximum values obtained from the parametric capacity curves. Therefore, a lower dispersion in the results is obtained when compared to *Scenario 1*. In these scenarios, the Column-Sway values can be considered as possible; however, if specific information about the structural weakness is collected and a soft-story mechanism is expected (e.g., presence of pilotis story), the Column-Sway values should be assumed as expected values. Finally, when a complete data acquisition is considered, the traditional seismic risk classification procedure can be applied. This leads to a single deterministic (expected) value for both IS-V and EAL. Again, results between Column-Sway and Mixed-Sway can still be considered as possible outcomes (or expected if specific structural weaknesses are observed/reported).



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

Figure 16. Example of performance points evaluation at Ultimate Limit State (ULS) in the ADRS domain (**a**) and EAL curves (**b**) for the case of incomplete data collection.

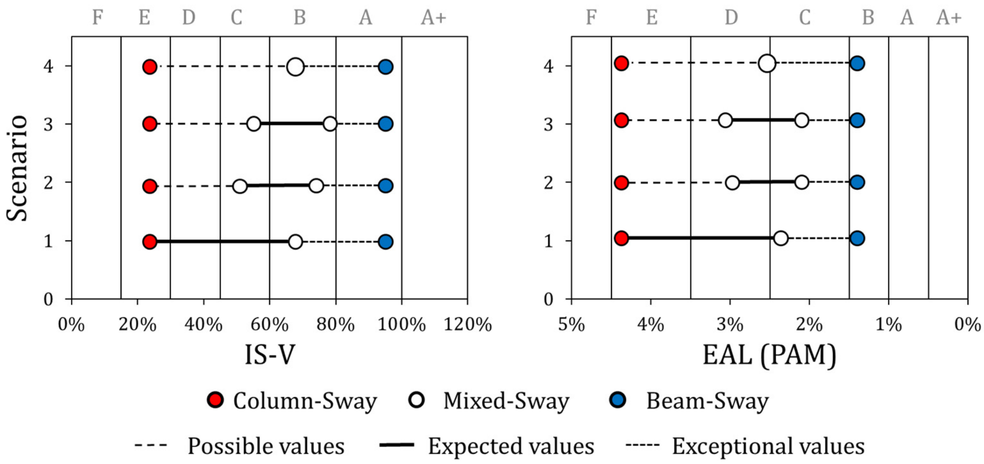


Figure 17. Example of possible, expected, and exceptional values of IS-V and EAL indices for each data acquisition scenario.

It is finally observed that the Beam-Sway results are deemed as exceptional values for each scenario. This information could be particularly useful to support the decision-making about retrofit strategies: (1) if the Beam-Sway values reach the targeted seismic performance/risk, a local inversion of the hierarchy of strength—protecting the joint panel zone and developing plastic hinges in the beams as the weakest link of the chain—can be considered as a valuable retrofit strategy; otherwise, (2) if the Beam-Sway results are below the targeted seismic performance/risk, strengthening retrofit strategies should be considered to enhance the seismic behavior. The latter typically involves the introduction of new structural members in the existing structure (e.g., shear walls).

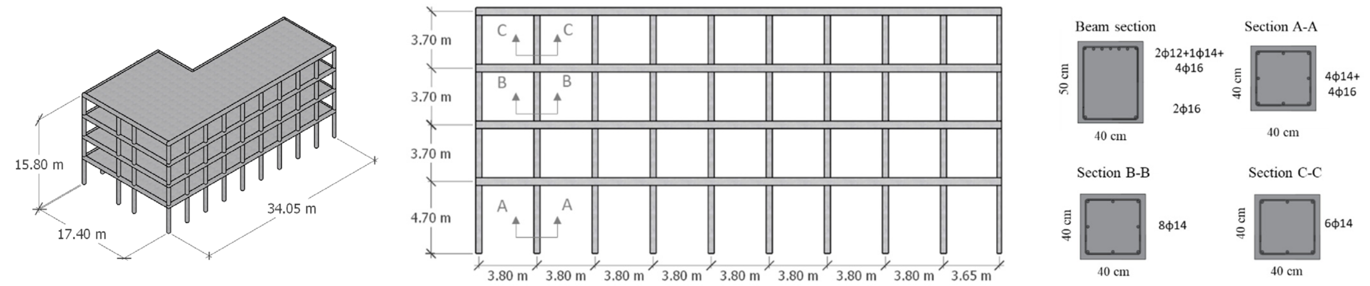
3.3. Illustrative Application to a School Building

In this section, the proposed SLaMA-based multi-knowledge assessment procedure is implemented for a case-study building for illustrative purposes. Firstly, a brief description of the selected case-study structure is provided. Different data collection scenarios are assumed in order to account for different building knowledge levels (i.e., different levels of available information). Results of the SLaMA analysis and the seismic risk classification are finally reported for each considered building knowledge scenario.

3.3.1. Description of the Case-Study Structure and Its Alternative Scenarios

The case-study structure consists of a four-storey Reinforced Concrete (RC) school building located in Lucera, South Italy (C soil type; Peak Ground Acceleration PGA = 0.252 g).

The selected building is part of a large data collection on school buildings located in the province of Foggia (South Italy), carried out under the UEFA/ELENA research project (Pampanin et al. [23]). Plan and global dimension of the case-study building are illustrated in Figure 18a.



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

Figure 18. Case-study school building: global view (**a**), geometric details of the analyzed RC frame (**b**), and geometric details of the RC members (**c**).

The structural skeleton is characterized by moment-resisting frames in both directions, with nine longitudinal bays and three transverse bays. Story masses are around 500 tons and 420 tons for a typical story and the roof, respectively. The construction period is 1972. Therefore, the structure is designed for gravity loads only (according to code provision of that construction period) and presents the typical structural weaknesses of existing buildings in Italy (e.g., lack of "capacity design" principles, inadequate transversal reinforcements, lower quality of materials). In this study, the proposed assessment methodology is implemented for the nine-bay longitudinal frame. The geometry of the frame is illustrated in Figure 18b, while geometric and reinforcement details of the RC members are shown in Figure 18c. The mean concrete compressive strength is 16.0 MPa, while the mean steel yield stress is equal to 392.0 MPa.

For the considered case-study building, information on geometry, structural details, and material properties are available from historical design documentations, architectural and structural drawings, tests on material samplings, and a photographic survey. However, for illustrative purposes only, four alternative building knowledge scenarios are assumed in order to implement the proposed methodology for basic-to-limited/incomplete building data collection. The case-study scenarios are the same described in the previous section, conceptually shown in Figure 13 and briefly listed below:

- *Scenario 1*: Basic building knowledge scenario. It is assumed that only information on the building geometry is available, while no data on either the reinforcement details or material properties are available/collected;
- *Scenario 2*: Limited/Incomplete building knowledge scenario. It is assumed that information on building geometry and material properties is available, while no information on the reinforcement details is available/collected;
- *Scenario 3*: Limited/Incomplete building knowledge scenario. It is assumed that information on building geometry and reinforcement details is available, while no information on the material properties is available/collected;
- *Scenario 4*: Complete building knowledge scenario. It is assumed that information on geometry, reinforcement details, and material properties is available/collected.

3.3.2. SLaMA-Based Nonlinear Static Analysis

The analytical-mechanical SLaMA procedure is implemented for each case-study scenario. As mentioned above, when basic or limited data collection scenarios are considered, assumptions are needed to account for the related uncertainties due to a lack of data/information. The main assumptions are herein discussed in detail.

Concerning *Scenario 1*, the reinforcement details of the structural members are identified through a "simulated" design, following the provision of the historical code of the construction period, i.e., "Regio Decreto" RD 2229 [38]. Due to the high uncertainty affecting this case-study scenario, conservative hypotheses are made, namely: (i) assuming the lowest quality of materials allowed by the historical code, when implementing the "simulated" design; (ii) considering the minimum amount of reinforcement and the weakest construction details, when performing the SLaMA analysis.

In *Scenario 2*, a "simulated" design is still needed to assess the reinforcement details of structural members, as for *Scenario 1*. Then, the minimum amount of reinforcement quantities evaluated through the "simulated" design is considered to identify alternative configurations by assuming different bar diameters and construction details. Specifically, three different amount of reinforcement quantities are selected for both beams and columns, involving the use of φ12, φ14, and φ16 bar diameters and different stirrups diameters (φ6, φ8) and spacings (150/200 mm). Moreover, three different construction details for the exterior beam–column joints are assumed based on the construction time of the building, that is, exterior joints without stirrups characterized by (i) beam longitudinal bars with hooked end anchorages, (ii) beam bars bent away from the joint, and (iii) beam bars bent into the joint. In conclusion, a total number of 108 parametric configurations are derived for *Scenario 2*. Therefore, by implementing the SLaMA analysis for each configuration, a range of pushover curves is obtained.

Considering *Scenario 3*, mechanical properties of materials are assumed referring to code/guidelines of the construction time and available information from the most relevant research works in literature. In this work, the results provided by Verderame et al. [36,37] for the mechanical properties of materials used in the pre-1976 period are considered. Specifically, the mean cylindrical concrete compressive strength is assumed as fc = 16.5 MPa with a Coefficient of Variation CoV = 0.15; the mean value of yield steel strength is assumed as fsy = 320 MPa with CoV = 0.08. As in Gentile et al. [39], nine equally spaced points in the range of $\mu \pm 2\sigma$ (μ = mean, σ = dispersion) are sampled for both concrete and steel strengths. This leads to a total number of 81 alternative configurations for *Scenario 3*.

Finally, *Scenario 4* represents a complete data acquisition scenario, i.e., all the data required for seismic assessment according to the main international codes are collected. Therefore, the SLaMA analysis is implemented without the need for any additional assumptions.

Figure 19 shows the SLaMA-based capacity curves obtained for each case-study scenario, together with the Beam-Sway (upper bound) and the Column-Sway (lower bound) capacity curves.

A mixed-sway mechanism (shown in Figure 19d), coupling external beam–columns joint failures with beam failures, characterizes the case-study frame (*Scenario 4*). As mentioned above, when dealing with limited data collection scenarios (i.e., *Scenario 2* and *Scenario 3*), the proposed multi-knowledge assessment procedure returns a range of possible capacity values/curves (108 and 81 parametric configurations are considered for *Scenario 2* and *Scenario 3*, respectively). Figure 19 also shows the normal (Gaussian) probabilistic distributions of the base shear values. In this case-study example, a higher dispersion is observed for *Scenario 2* when compared to *Scenario 3*. This result is in line with other research studies in literature (e.g., [3,39]), further confirming that the seismic performance of the building is more sensitive to the structural/reinforcement details than to materials properties. On the other hand, it can be noted that no significant modifications are observed in terms of ultimate displacement capacity when comparing the case-study scenarios. This is due to the observed plastic mechanisms, where the ultimate displacement of the structure is limited by the Life Safety deformation capacity of external joints in all scenarios. Finally, due to the high uncertainties affecting *Scenario 1*, the range of possible capacity values is assumed to be limited by the Column-Sway and Mixed-Sway capacity curves.

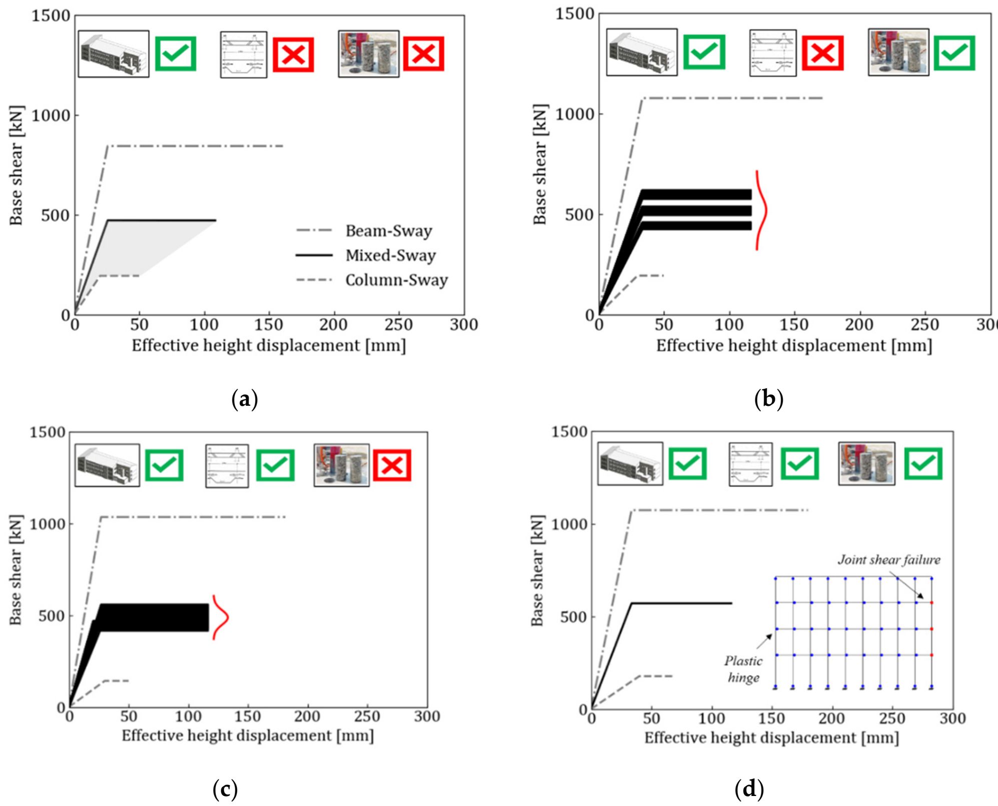


Figure 19. SLaMA-based pushover capacity curves for all case-study scenarios: *Scenario 1* (**a**), *Scenario 2* (**b**), *Scenario 3* (**c**), and *Scenario 4* (**d**).

3.3.3. Seismic Risk Classification

The results of the SLaMA analysis are used to assess the seismic risk class for each case-study scenario, according to the Italian seismic risk classification, exhaustively discussed in the previous sections. The Capacity Spectrum Method [10] is applied in order to assess the building performance at different seismic demand intensity. Then, for each case-study scenarios, possible, expected, and exceptional values of both IS-V and EAL indices are assessed following the procedure explained in the previous sections. Results in terms of both IS-V and EAL indices are shown in Figure 20. Moreover, expected values of both indices are listed in Table 1.

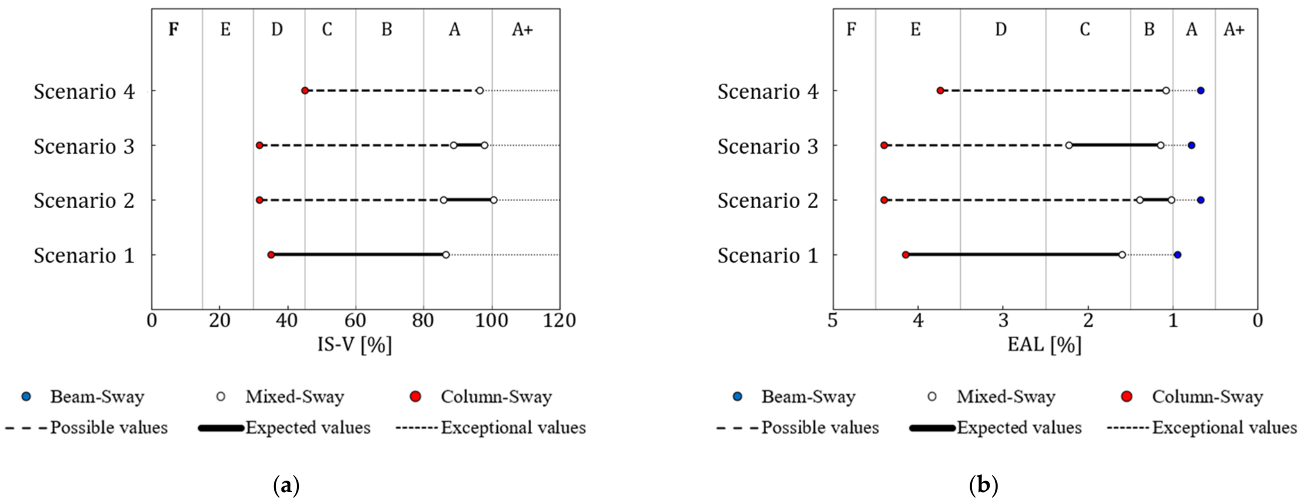


Figure 20. IS-V (**a**) and EAL (**b**) values for each considered scenario.

Table 1. Expected values of IS-V and EAL indices for each considered scenario.

	IS-V [%]	IS-V Class	EAL [%]	EAL Class	Seismic Risk Class
Scenario 1	35–86%	D_{IS-V}–A_{IS-V}	4.14–1.59%	E_{EAL}–C_{EAL}	E–C
Scenario 2	86–100%	A_{IS-V}–$A+_{IS-V}$	1.39–1.17%	B_{EAL}	B
Scenario 3	89–98%	A_{IS-V}	1.15–2.22%	C_{EAL}–B_{EAL}	C–B
Scenario 4	96%	A_{IS-V}	1.08%	B_{EAL}	B

Results generally highlight a good seismic performance of the case-study structure (seismic risk class "B" for Scenario 4, i.e., complete data collection), even if the building was designed for gravity loads only. This is mainly due to the moderate seismicity of the site. Moreover, it is worth highlighting that, in this illustrative application, only the longitudinal nine-bay frame is considered, while the transversal three-bay frame may lead to higher seismic vulnerability of the building.

Results shown in Figure 20 and listed in Table 1 preliminarily confirm the effectiveness of the proposed methodology, leading to similar seismic risk classes for the case of limited data collection (i.e., *Scenario 2* and *Scenario 3*) when compared to a complete data collection scenario (i.e., *Scenario 4*). Although *Scenario 1* provides the highest dispersion of expected values, results are still deemed useful for a preliminary assessment of the buildings. The assessment outcomes could indeed support the decision-making process on more detailed inspection aiming to improve the building knowledge and address the design of retrofit interventions in order to resolve specific critical structural weaknesses.

3.4. Adaptive Seismic Risk Assessment of School Building Portfolio at Regional and/or National Level

As future step, the proposed PELL-School-RS form and multi-knowledge SLaMA-based assessment procedure can support the definition of fragility and vulnerability models for large-scale applications and, consequently, the development of seismic risk maps. Focusing on the Italian scenario, the last National Risk Assessment (NRA) [41,42] was developed in 2018 by the Department of Civil Protection (DPC), and the IRMA (Italian Risk MAps) platform [43] was used to perform the calculation. IRMA uses OpenQuake calculation engine [44] to evaluate the seismic risk maps, allowing the user to define/upload different exposure and vulnerability models, as well as different sets of fragility relationships for building classes. Being the seismic risk defined as the convolution of the seismic hazard with vulnerability and exposure, the adopted assumptions for each of the three physical parameters are briefly described below:

- *Seismic hazard:* the official hazard map for the Italian code regulation (Stucchi et al. [45]) was adopted. As a simplified hypothesis, the same soil type was assumed over the whole Italian territory (i.e., soil type "A": rock or stiff soil category).
- *Vulnerability:* five vulnerability classes are defined, namely, "A", "B", "C1", "C2", and "D" (vulnerability decreases from "A" to "D"), according to the EMS-98 [28] classification. For each vulnerability class, a set of five fragility curves is defined, corresponding to the probability of exceeding five different Damage States (DSs), from D_1 to D_5, defined following the EMS-98 scale.
- *Exposure:* the ISTAT database [46,47] is adopted to define the building typologies, considering construction material, number of floors, and construction age. Then, at municipality levels, each building typology is associated with one or more vulnerability classes, through a specific vulnerability-exposure model.

Risk in terms of damage was thus evaluated according to Equation (1):

$$\lambda_k = \int_0^{\infty} P(D_k \big| im) \cdot |d\lambda_{IM}(im)| \quad (1)$$

where $P(D_k|im)$ is the probability of exceeding a D_k damage state given a ground motion intensity measure im, and $\lambda_{IM}(im)$ is the Mean Annual Frequency (MAF) of the exceedance of a ground motion intensity *im*. Finally, risk in terms of consequences (i.e., direct economic losses, unusable buildings, and casualties) was evaluated by defining damage-to-impact rules. The last NRA was developed through a multi-model methodology, involving five different research units, where each research unit proposed a vulnerability/exposure model. Specifically, four models were developed for masonry buildings [48–51] and two for RC buildings [52,53]. Fragility functions for the vulnerability models were developed adopting empirical [48,51,52], analytical [50,53], or hybrid [49] approaches. Results were finally combined by aggregating the outputs of two or more vulnerability and exposure models, by a simple joint of results of models concerning different material types or by using specific weights for models concerning the same building typology.

Based on the work developed so far, the methodology herein proposed and developed within the PELL project could provide support for the development and further advancements of the NRA. On one hand, the PELL-Seismic-RS form could be used to collect useful information on the Italian building stock, involving data on the seismic-resistant structure and on the possible presence of Critical Structural Weaknesses, CWS. Considering the interoperability of the PELL platform, this could become a reference database for different building typologies (not only school buildings), thus providing additional relevant structural information that are not available in the ISTAT census. Moreover, in addition to a seismic assessment of building stock based on statistical data (e.g., ISTAT database), an important step toward a building-to-building seismic assessment could be conducted at national level.

On the other hand, a vulnerability model, with associated fragility functions, can be developed using the proposed multi-knowledge, SLaMA-based assessment procedure. Specifically, the output of SLaMA results (i.e., pushover capacity curves and associated local and global mechanisms) can be employed to develop fragility relationships according to the state-of-the-art methodologies for pushover-based fragility analysis (e.g., [25,54–56]). Should a more refined seismic response analysis be preferred, the SLaMA method can also be used to define the backbone curves of equivalent Single-Degree-of-Freedom (SDoF) models and develop fragility relationships through nonlinear dynamic (time history) analyses, in line with other research works available in literature (e.g., [57]). Furthermore, the plastic mechanism expected/predicted by the SLaMA method can be used to define the hysteretic behavior of the equivalent SDoF model (e.g., if the observed plastic mechanism involves joint failures, a hysteretic behavior characterized by a severe pinching effect is deemed more suitable for the equivalent SDoF model). In this way, a seismic-risk assessment accounting for the specific characterization of the hazard in different Italian locations (thorough an adequate record selection) can be carried out. Recent investigations [58] have shown that the SLaMA method provides a relatively good level of accuracy in estimating the median and the dispersion of fragility relationships both using spectrum-based approaches or nonlinear dynamic analysis (error between $\pm 20\%$ with respect to nonlinear time-history analysis on a Multi-Degree-of-Freedom, MDoF, model of the structure). When limited building knowledge is available, an uncertainty-based range/domain of fragility curves can be obtained. Following this approach, a vulnerability model can be developed based on the material/documentation available for the building. Therefore, a different set of fragility functions can be associated with each knowledge level. Then, combining the fragility analysis with the hazard analysis, the seismic risk of the structure can be assessed in terms of MAF of exceeding a specific Damage State, DS (Figure 21).

Finally, results can be derived in terms of causalities, still accounting for different knowledge levels. A reduction in the result dispersion could be obtained once more detailed information becomes available. In this way, a dynamic and adaptive seismic risk maps for Italian school buildings could be developed.

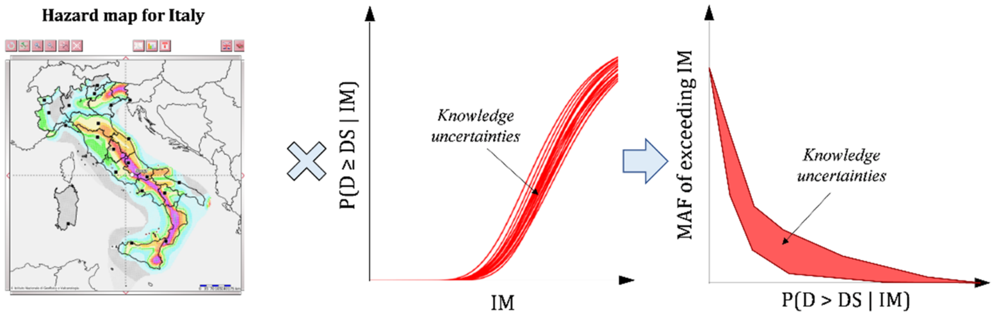


Figure 21. Example of seismic risk calculation in terms of Mean Annual Frequency, MAF, of exceeding a specific Damage State, DS, accounting for building knowledge uncertainties (hazard map for Italy available online: http://esse1-gis.mi.ingv.it/, accessed on 5 July 2022).

4. Conclusions

The paper presented a framework and adaptive tool for multi-knowledge seismic risk assessment of school buildings. Particular focus was firstly given to the development of an ad-hoc assessment form, which replicates the data structure of existing official forms defined by the Italian Presidency of the Council of Ministers, Department of Civil Protection, and the New Zealand Ministry of Business Innovation and Employment, and includes additional input data in order to properly identify the relevant building information, as well as the possible structural weaknesses. These data allow for an estimation of the seismic risk class and the expected mean annual loss of school buildings, before (as-built conditions) and after seismic retrofitting interventions. To this end, a multi-knowledge seismic assessment procedure was proposed and presented. The procedure is based on the analytical-mechanical SLaMA (Simple Lateral Mechanism Analysis) method and allows one to perform a seismic assessment of school buildings without the need for time-consuming numerical analyses. Considering the simplicity of the SLaMA method, the procedure can be easily implemented considering different or increasing levels of building knowledge, thus directly accounting for the related uncertainties. When a limited or incomplete data acquisition level is available, the multi-knowledge assessment procedure returns a range of possible capacity values/curves. The dispersion in the results can be narrowed when more data on the building becomes available. By comparing the capacity curve of the structure and the seismic demand in the ADRS domain, the Safety Index and the Expected Annual Losses can be evaluated, according to the Italian code provisions. This allows to develop a standardized tool to be implemented in the "Seismic-Response" module of the PELL (Public Energy Living Lab)-School platform, aiming to become a standardized and interoperable database for the collection of relevant data for the seismic assessment and monitoring of Italian schools. By identifying the seismic risk classification of school buildings based on the achievable knowledge level, it is conceptually possible to overcome the issue related to limited building information. The procedure was implemented for a case-study school building for illustrative purposes. Results confirmed the effectiveness of the procedure, allowing us to evaluate the range of expected seismic risk classes based on different/increasing level of building knowledge. The approach allows for a continuous update of the information collected for each school and a reduction in the uncertainties in the seismic risk assessment outcomes as further data/information becomes available. Therefore, the proposed framework could be adopted to support the definition of a prioritization plan at national level and develop large-scale (territorial, regional, national) seismic risk analyses. It is worth highlighting that the procedure can be coupled and implemented with the most relevant vulnerability assessment forms at international level and could become a main step in the assessment and rehabilitation process of the existing building stock.

Although this research work represents a promising preliminary step toward an improved data collection and seismic risk classification of Italian schools, it is worth mentioning that research efforts are still needed to further validate the proposed procedure. Specifically, research work is needed to implement the multi-knowledge assessment procedure in the PELL-School platform and provide a user-friendly tool for seismic risk assessment of Italian schools.

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