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Adaptive knowledge-based seismic risk assessment of existing reinforced concrete buildings using the SLaMA method

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Abstract

This paper presents and discusses the ongoing developments towards the definition of a multi-knowledge level seismic assessment procedure for large-scale seismic risk applications. The procedure involves the analytical-mechanical SLaMA (Simple Lateral Mechanism Analysis) method and allows for an adaptive and updatable assessment of the seismic performance of buildings accounting for different data acquisition (knowledge) levels. By coupling this approach with vulnerability assessment survey forms, a range/domain of expected capacity curves of a structure can be obtained and used to evaluate the seismic safety and the expected economic losses according to the state-of-the-art procedures in literature. Moreover, the results of the analytical assessment method can be used to develop fragility curves through simplified spectrum-based procedures. Combining the results of the fragility analysis with the hazard analysis, the seismic risk of a structure can be assessed in terms of Mean Annual Frequency (MAF) of collapse, as well as in terms of Expected Annual Losses (EAL). The proposed SLaMA-based approach is illustrated for an existing reinforced concrete building. Results confirm the effectiveness of the methodology for seismic-risk assessment studies at large scale, thus overcoming the issue related to limited building information, yet allowing for a continuous update of the "digital twin" model as further data/information becomes available.

Keywords: Seismic risk; school buildings, fragility analysis; data uncertainty; economic losses.

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1. Introduction

The crucial need to reduce the socio-economic consequences and impacts of earthquake events through the implementation of seismic risk reduction strategies at national level has been further emphasized by recent catastrophic earthquakes (e.g., L'Aquila 2009; Emilia 2012; Central Italy 2016). Focusing on the Italian scenario, the financial incentives for seismic retrofitting interventions on existing buildings recently introduced by the Italian government and referred to as "Sismabonus" (DM 65 2017, Cosenza et al. 2018) represent a unique opportunity to improve the seismic performance of the Italian building stock (Cosenza et al. 2018, Pampanin et al. 2021). A fundamental step towards the implementation of a medium-to-long-term national plan of seismic risk reduction consists of the definition of a prioritization plan at national scale, based on a Detailed Seismic (vulnerability) Assessment (DSA) of the built environment in terms of both life-safety and expected economic losses. However, the evident complexity in the data acquisition of the building stock, as well as the need for improved and standardized tools and procedures for seismic vulnerability analysis of existing buildings are often deemed as primary obstacles to the implementation of such an ambitious plan (Pampanin et al. 2017).

In line with this goal, the analytical-mechanical SLaMA (Simple Lateral Mechanism Analysis; NZSEE2017) method could be adopted as an effective and standardized tool for the seismic assessment of buildings at large scale. This procedure is an analytical-mechanical method developed "by hand" (i.e., by using a spreadsheet), rather than, and prior to, a numerical finite element analysis (Pampanin 2017). As shown in Fig. 1, the SLaMA method allows evaluating the pushover (force-displacement) capacity curve and the expected plastic mechanism by assessing the hierarchy of strength at the sub-assembly level. The building performance under different earthquake intensity levels can be thus evaluated by a Capacity/Demand comparison in the Acceleration Displacement Response Spectra (ADRS) domain, in line with the Capacity Spectrum Method (CSM, ATC 40 1996). Despite the simplicity of the method, several analytical-numerical comparisons (e.g., Del Vecchio et al. 2018; Gentile et al. 2019; Bianchi et al. 2019) have highlighted that the SLaMA procedure leads to satisfactory results when compared to numerical analysis.

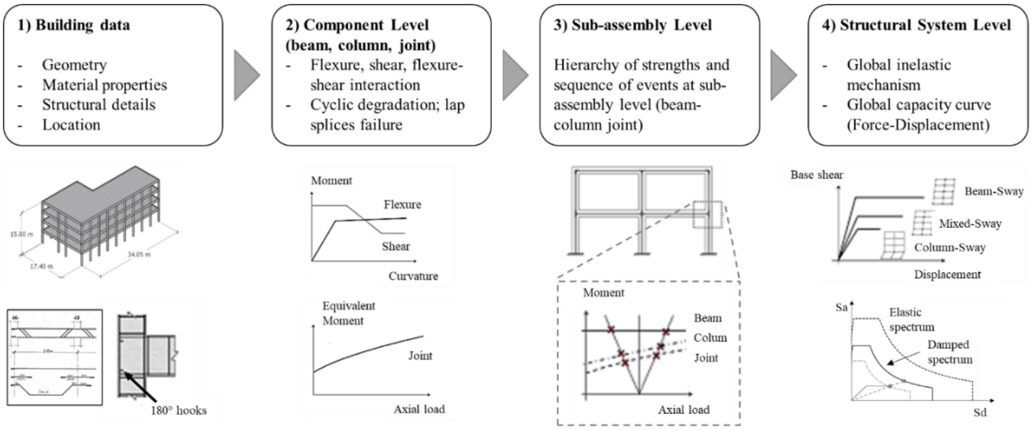


Fig. 1. Flowchart of the analytical-mechanical SLaMA procedure (modified after Pampanin 2017).

To overcome the issue related to limited building knowledge, this paper proposes a SLaMA-based multi-knowledge level seismic assessment procedure for large-scale seismic-risk applications. The proposed procedure allows for an adaptive and updatable assessment of the seismic performance of buildings accounting for different data acquisition (knowledge) levels. Data collected through ad-hoc vulnerability assessment survey forms can be processed and used as input data of the SLaMA-based procedure, returning a range/domain of expected capacity curves of the structure when limited building knowledge is achieved. The results of the analytical assessment method can be used to assess the seismic safety and the economic losses of the structure. Therefore, a preliminary evaluation of the probable building capacity can be obtained, subsequently results can be further improved should additional data become available. To prove this concept, this paper presents an application of the procedure to a case-study Reinforced Concrete (RC) frame structure assuming different building knowledge levels.

2. Methodology

The adopted research methodology is illustrated in Fig. 2. Each step is herein described in detail.

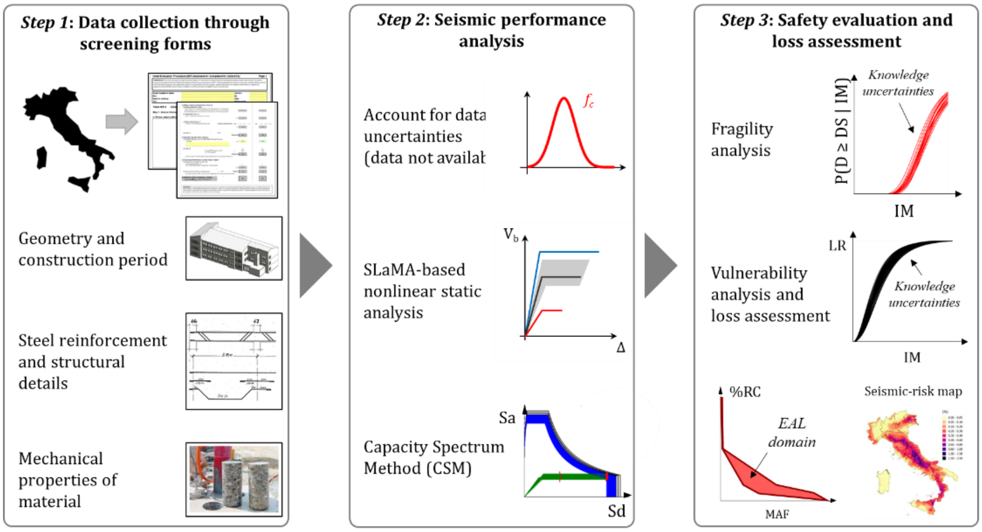


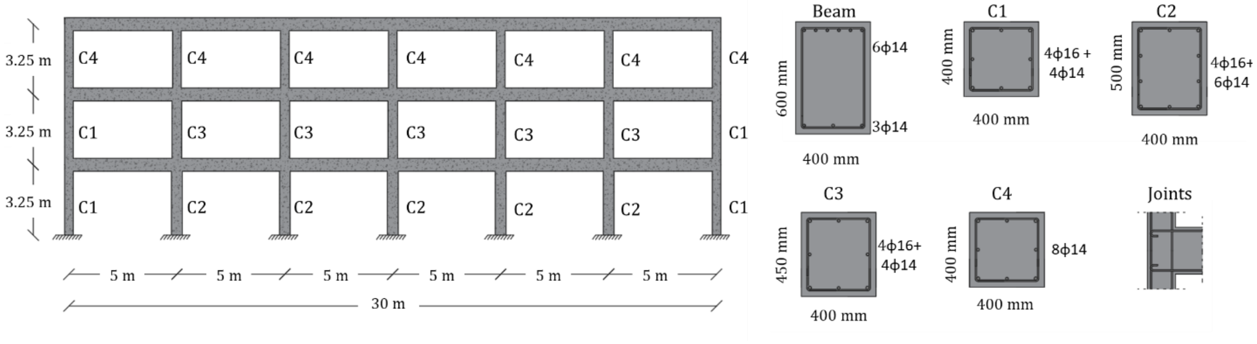
Fig. 2. Flowchart of the research methodology.

In seismic risk assessment applications, the first fundamental step is the identification of relevant building data (i.e., geometry, material properties and structural details) as well as critical structural weaknesses that can potentially affect the seismic performance of the structure (*Step 1*). Therefore, the proposed adaptive knowledge-based assessment procedure should be coupled with an ad-hoc vulnerability assessment form involving the information on the data source and the available documentation, in order to properly consider the reliability of the data collected and, consequently, the related uncertainties. Then, the information collected and compiled through the assessment forms can be processed and used to assess the seismic performance of the building (*Step 2*). If limited information is collected, assumptions/calculations are needed to perform the analysis and uncertainties (in both materials and/or structural details) should be considered in either deterministic (parametric) or probabilistic (mathematical distributions) approaches. Specifically, assumptions should be made based on codes or guidelines of the design/construction time of the structure and according to the most relevant literature research works at both national and international levels. When introducing uncertainties due to limited building information, parametric configurations, rather than a single configuration, can be investigated and, consequently, a range/domain of possible capacity curves can be obtained. As mentioned above, in the proposed procedure, the analytical-mechanical SLaMA method (NZSEE 2017) is adopted to perform the seismic analysis of the structure. As a matter of fact, this analytical procedure is deemed as an effective tool for large-scale applications as well as when different levels of building knowledge are involved. The results of the SLaMA are used to perform a fragility analysis (*Step 3*) in line with the state-of-the-art procedures for nonlinear static (pushover) analysis (e.g., Vamvatsikos and Cornell 2006, FEMA P-58 2012, Bianchi et al. 2019, Nettis et al. 2021). By performing the fragility analysis for each capacity curve, a range of fragility curves is obtained for different damage states (from slight to complete damage). A damage-to-loss model, correlating the damage states with their loss ratio, is adopted to convert the fragility curves into vulnerability functions (Gentile and Galasso 2021, Martins and Silva 2021). More details about the formulations adopted for fragility and vulnerability analyses are provided in the following section. Finally, by combining the results of the fragility analysis with the hazard analysis, the seismic risk of the structure can be assessed in terms of Mean Annual Frequency (MAF) of collapse, as well as in terms of Expected Annual Losses (EAL). The final output thus consists of a range of values for both the collapse risk and the EAL. In the next section, the proposed SLaMA-based multi-knowledge assessment methodology is illustrated for an existing reinforced concrete case-study building.

3. Application to a case-study building

3.1. Description of the building and case-study scenarios

The proposed SLaMA-based multi-knowledge assessment procedure is implemented for a RC frame structure for illustrative purposes. The case-study frame is extracted from a 3-story school building located in Lucera, South Italy, (C soil type; Peak Ground Acceleration PGA = 0.252g), as part of a large data collection carried out for the UEFA/ELENA research project (Pampanin et al. 2020). Geometric details of the frame are shown in Fig. 3.



(a) (b)

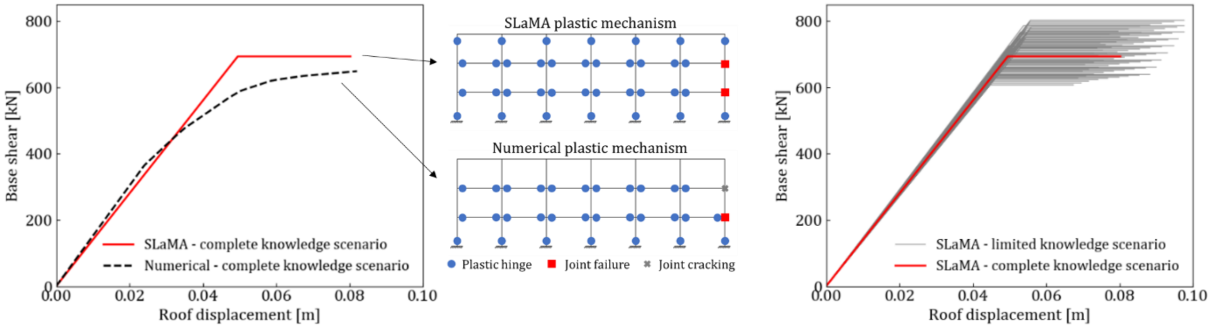
Fig. 3. (a) Geometric details of the analysed RC frame and (b) its structural members – C1-4: columns and Beam.

Story mass is around 340 tons and 260 tons for a typical floor and the roof, respectively. The structure was designed and built in the period 1961-1973. Therefore, it presents the typical structural weaknesses of existing buildings designed for gravity loads only (e.g. lack of "capacity design" principles). Data on mechanical properties of materials and reinforcement details are available from tests on material samplings and in-situ inspection (pacometric investigations), respectively. Specifically, the mean concrete compressive strength is 16.0 MPa, while the mean steel yield stress is equal to 310.0 MPa. The reinforcement details of structural members are shown in Fig. 3 (b). The joints are characterized by no stirrups and beam longitudinal bars with hooked end anchorages.

Although the information on the material properties and reinforcement details is available for the selected frame structure, an alternative building knowledge scenario is assumed to implement the SLaMA-based multi-knowledge assessment procedure. Specifically, in addition to complete building knowledge in terms of geometric properties and structural details, it is assumed that no information on the material properties is collected. Therefore, assumptions are needed to account for this limited data collection. To this end, mechanical properties of typical materials used in pre-1970s buildings can be assumed according to Verderame et al. (2001a,b), namely: a mean value fc=16.5 MPa and a Coefficient of Variation CoV=0.15 for the concrete compressive strength, while a mean value of fsy=320 MPa with CoV=0.08 for the steel yield strength. For both concrete and steel strengths, nine equally spaced points in the range of $\mu \pm 2\sigma$ (μ=mean, σ=dispersion) are sampled (as in Gentile et al. 2021), leading to a total of 81 alternative configurations simply referring to variation of the material properties, for a given knowledge level on the geometric properties and structural details.

3.2. SLaMA-based pushover analysis

Results in terms of SLaMA-based capacity curves for both scenarios (complete and limited data acquisition) are presented in Fig. 4. Furthermore, to validate the accuracy of the analytical approach, Fig. 4a shows a comparison between the SLaMA-based capacity curve and the pushover curve obtained through a numerical finite element analysis for the complete data collection scenario. Specifically, a two-dimensional (2-D) lumped-plasticity model is implemented in the software Ruaumoko2D (Carr 2016) and nonlinear static analysis is performed to derive the building capacity curve. More details about the adopted modelling approach can be found in Pedone et al. (2021).



(a) (b)

Fig. 4. SLaMA vs. numerical capacity curves and plastic mechanism for (a) complete data collection scenario, and (b) analytical pushover curves obtained for limited and complete knowledge scenarios.

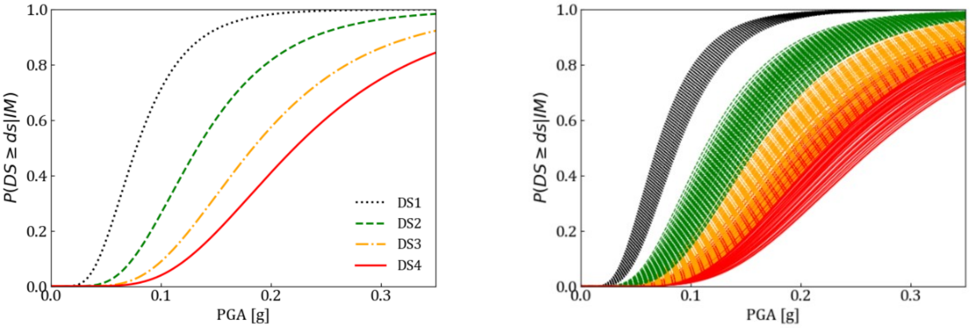
Due to the lack of capacity-design principles, the plastic mechanism of the building is a mixed-sway mechanism, characterized by external beam-columns joint failures coupled with beams failures. The analytical-numerical comparison highlights a good agreement when considering the simplicity of the SLaMA method. Particularly, the initial stiffness is well captured, the difference between the analytical and numerical base shear is less than 7%, while the local mechanisms predicted by the SLaMA are in good agreement with the numerically-predicted plastic mechanism. As mentioned above, when limited data collection is available, the SLaMA-based assessment procedure allows to identify a range of possible capacity curves. In this work, 81 configurations are analyzed and a range of seismic capacity curves is obtained (Fig. 4b). It can be noted that the pushover curve obtained from a complete data collection (red curve in Fig 4b) is included in the range of expected values for strength and displacement capacity.

3.3. Fragility and vulnerability analysis

The results of the SLaMA-based pushover analysis are used to perform fragility and vulnerability analyses, whose main steps are discussed below. The same procedure is applied for each capacity curve.

Firstly, the force-displacement pushover curve is converted into the ADRS format following the NZSEE (2017) provisions. Four different building-level Damage States (DSs) are then defined, namely: DS1 (slight damage), DS2 (moderate damage), DS3 (extensive damage), and DS4 (complete damage). DSs thresholds are defined as a function of the ultimate (d_u) and the yielding (d_y) displacements of the capacity curve, according to Martins and Silva (2021): $d_{DS1} = 0.75d_y$; $d_{DS2} = 0.5d_y + 0.3d_u$; $d_{DS3} = 0.25d_y + 0.67d_u$; $d_{DS4} = d_u$. However, different criteria can be adopted. Then, the DS thresholds expressed in terms of spectral displacement are converted into equivalent values PGA by applying the CSM (ATC-40 1996) as suggested in the HAZUS methodology (Kircher et al. 2006). Specifically, the demand (code-compliant) spectrum is scaled uniformly in order to intersect the capacity curve at the DS spectral displacement of interest. The PGA of the scaled spectrum defines the median value of the fragility. Fragility curves are assumed to follow a lognormal cumulative probability function, characterized by a median PGA value and a dispersion value β. The latter is evaluated according to the FEMA P-58 (2012) where values of dispersion are provided as a function of the building fundamental period (T_1) and the strength ratio (S).

The obtained fragility curves for both the complete and limited data collection scenarios are shown in Fig. 5. Median (μ_{DS}) and standard deviation (β_{DS}) values are listed in Table 1, where both minimum and maximum values of μ_{DS} and β_{DS} are listed for the limited data collection scenario. Moreover, fragility estimation is also carried out for the numerical pushover curve and the results are still listed in Table 1.



(a) (b)

Fig. 5. SLaMA-based fragility curve for the (a) complete and (b) limited data collection scenarios.

Table 1. Median and standard deviation values of fragility curves for complete and limited data collection scenarios.

	DS1		DS2		DS3		DS4	
	μ_{DS} $[g]$	β_{DS}	μ_{DS} $[g]$	β_{DS}	μ_{DS} $[g]$	β_{DS}	μ_{DS} $[g]$	β_{DS}
Numerical (CDCS)	0.072	0.462	0.121	0.462	0.167	0.462	0.202	0.462
SLaMA (CDCS)	0.078	0.452	0.133	0.452	0.184	0.452	0.222	0.452
SLaMA (LDCS)	0.069-0.088	0.437-0.468	0.113-0.16	0.437-0.468	0.155-0.222	0.437-0.468	0.187-0.268	0.437-0.468

Notes: CDCS = Complete Data Collection Scenario; LDCS = Limited Data Collection Scenario.

Table 1 shows that similar median and standard deviation values are obtained when comparing the results of the SLaMA with the numerical analysis. An error smaller than 10% and 2% is in fact observed for the median and standard deviation, respectively. Moreover, the median and dispersion values of the complete data collection scenario (both numerical and SLaMA) are contained within the range of values evaluated for the limited data collection scenario, consistently with the proposed multi-knowledge assessment methodology.

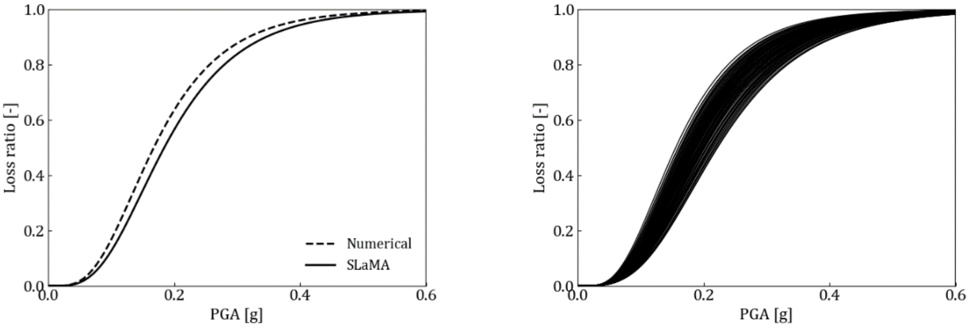
Vulnerability analysis is performed by adopting the building-level damage-to-loss model proposed by Martins and Silva (2021). For the sake of simplicity, only the mean values (i.e., percentage of repair/reconstruction cost) are considered. Specifically, a Loss Ratio (LR_i) equal to 5%, 20%, 60%, and 100% is considered for DS1, DS2, DS3, and DS4, respectively. Nevertheless, it is worth noting that different damage-to-loss models can be adopted.

Vulnerability curves are finally derived through Eq. (1):

$$LR(IM) = \sum_{1}^{4} P(DS = ds_i|IM) \cdot LR_i \tag{1}$$

where $P(DS = ds_i|IM)$ is the probability of attaining a damage state ds_i given an Intensity Measure (IM) value.

Fig. 6 shows the results of the vulnerability analysis for both the completed and limited data collection scenarios.



(a) (b)

Fig. 6. Vulnerability functions for the complete (a) and limited (b) data collection scenarios.

3.4. Safety evaluation and loss assessment

Finally, the results of the fragility and vulnerability analyses are combined with the hazard curve to perform seismic safety evaluation and loss assessment of the case-study structure. Specifically, the Italian seismic hazard model (Stucchi et al. 2011) is herein adopted. Seismic safety is assessed in terms of MAF of collapse. In this research work, a refined version of the SAC/FEMA (Cornell et al. 2002) closed-form expression is adopted, considering a second-order power-law hazard fit proposed in Vamvatsikos (2013).

Concerning the loss assessment, the EAL index is evaluated starting from the results of the vulnerability analysis through Eq. (2), according to Gentile and Galasso (2021):

$$EAL = \int_0^{\infty} LR(IM = x) \left| \frac{d\lambda_{IM}(x)}{dx} \right| dx \tag{2}$$

where $LR(IM = x)$ is evaluated through Eq. (1). In order to avoid large extrapolations, the integration is limited to events with a return period contained in the range of 10 and 100’000 years.

Results of the safety evaluation and loss assessment are reported in Table 2.

Table 2. Results in terms of Mean Annual Frequency (MAF) of collapse and Expected Annual Losses (EAL)

	MAF of collapse	EAL [%]	EAL Class (DM 65 2017)
Numerical (CDCS)	$3.38{\cdot}10^{-3}$	0.667	$\mathrm{A_{EAL}}$
SLaMA (CDCS)	$2.60{\cdot}10^{-3}$	0.535	$\mathrm{A_{EAL}}$
SLaMA (LDCS)	$1.50{\cdot}10^{-3}$ - $4.1{\cdot}10^{-3}$	0.346 - 0.784	$\mathrm{A+_{EAL}}$ - $\mathrm{A_{EAL}}$

Notes: CDCS = Complete Data Collection Scenario; LDCS = Limited Data Collection Scenario

A good agreement in the results of the numerical analysis and the SLaMA method is observed in terms of both MAF of collapse and EAL. Specifically, an error equal to almost 23% and 20% is obtained in the results for the MAF of collapse and the EAL, respectively. Table 2 also shows that the results obtained for the complete data acquisition scenario (both numerical and SLaMA) are contained in the range of values assessed for the limited data collection scenario, both in terms of MAF of collapse and the EAL. Table 2 also shows the results of the seismic classification in terms of EAL classes obtained referring to the Italian seismic risk classification, DM 65 (2017). In this document, eight different classes are defined (from “$\mathrm{A+_{EAL}}$” to “$\mathrm{G_{EAL}}$”, where “$\mathrm{A+_{EAL}}$” represents the highest seismic performance) based on the EAL index. Results highlight that the same EAL class (“$\mathrm{A_{EAL}}$”) is obtained using the numerical and the SLaMA pushover curves for the complete data collection scenario. Moreover, a similar range of EAL classes (“A+” - “A”) is assessed considering the limited data collection scenario. Although the case-study building is designed for gravity load only, results highlight a relative good seismic performance of the structure, however this is mainly due to the moderate seismicity of the site. Finally, it is worth noting that the Italian seismic risk classification is herein used only as an example of a possible definition of building performance classes.

4. Conclusions

In this paper a multi-knowledge level seismic assessment procedure for large-scale seismic risk applications has been proposed and discussed. The procedure is based on the analytical-mechanical SLaMA (Simple Lateral Mechanism Analysis) method and allows for an adaptive and updatable assessment of the seismic performance of buildings without the need for numerical (computer-based) analyses. The SLaMA-based methodology was implemented for an existing RC building for illustrative purposes, assuming different data collection scenarios (i.e., different building knowledge levels). Results highlighted that the proposed methodology allows evaluating the range of expected vulnerability values (both in terms of mean annual frequency of collapse and Expected Annual Losses, EAL) based on different levels of building knowledge. Moreover, the SLaMA vs. numerical comparison returned a good agreement in the results. The proposed SLaMA-based multi-knowledge level seismic assessment methodology can support seismic-risk assessment studies at large scale, when limited building information is available. Moreover, by coupling the procedure with ad-hoc vulnerability assessment survey forms, an adaptive, incremental an updatable tool can be developed, providing a preliminary seismic assessment of the structures and able to reduce the uncertainties in the results when more data/information becomes available. Despite the potential of the outputs presented in this research work, future investigations are needed to further validate the proposed methodology.

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