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PRIORITIZATION METHODOLOGY FOR SEISMIC RETROFITTING OF HETEROGENEOUS BUILDING STOCKS

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Abstract

A comprehensive assessment of seismic risk across large, diverse building portfolios is essential for effective asset management in earthquake-prone areas. Yet, existing methods often target specific building types or asset classes, limiting their broader applicability. This study introduces a flexible and integrated methodology suitable for evaluating mixed building stocks—including masonry, reinforced concrete (RC), precast reinforced concrete (PRC), and steel structures. The approach combines qualitative assessments based on observed deficiencies with simplified mechanical models, ensuring a consistent evaluation across all structural types. Where established tools were lacking, new ones were developed to maintain methodological coherence. The framework was tested on an industrial building portfolio of 80 structural units located in Italy, effectively identifying priority structures for retrofitting. By overcoming the limitations of type-specific methods, this approach enables a more unified and scalable assessment process. It supports strategic decision-making and prioritisation, ultimately contributing to improved seismic risk mitigation and increased resilience on a regional scale.

Keywords: Prioritisation, Decision-making, Survey forms, Simplified mechanical model, Heterogeneous building stocks.

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1 INTRODUCTION

Seismic risk assessment of large building stocks is a key challenge in earthquake-prone areas. Efficiently prioritising interventions for retrofitting and strengthening existing structures requires rapid, cost-effective evaluation methods. This is crucial for effective asset management and for optimising resource allocation by stakeholders, including property owners, companies, and public administrations. Prioritisation is not only necessary for retrofitting but also for planning structural investigations required by various regulations. These investigations are often expensive, invasive, and disruptive, especially in industrial settings. Therefore, a structured approach is needed to minimise economic and operational impacts. Several approaches to prioritisation and territorial vulnerability assessment have been proposed, with methods tailored to different scales of analysis. Mass-appraisal techniques aim at assessing large-scale built heritage or numerous individual assets [1-7]. These methods generally rely on sparse census data, associating structures with broad macro-classes and assuming homogeneous seismic vulnerability within these classes. However, such approaches are inadequate for prioritising at the building stock level, where a more detailed assessment of individual building features is necessary. Rapid Visual Screening (RVS) is a widely used method that provides preliminary evaluations with minimal cost and time. Several national institutions have developed RVS forms designed for masonry and reinforced concrete buildings [8-10]. Recent studies have adapted RVS for specific building types, such as reinforced concrete hospitals and schools, incorporating both structural and non-structural vulnerabilities and organisational features that impact emergency response [11, 12]. These adaptations have been enhanced through multi-criteria analysis and fuzzy logic, offering a more comprehensive evaluation [13]. In addition to RVS, simplified mechanical models are used for rapid seismic vulnerability assessments, especially for unreinforced masonry buildings. Tools like Vulnus and DBV-masonry are commonly used for the seismic assessment of historical buildings [14–16]. For reinforced concrete (RC) buildings, simplified methods based on non-linear analyses [17] or displacement-based assessment [18-20] are available, although these are often restricted to 2D representations or only applicable to RC frames, excluding other structural systems. To improve assessment reliability, multi-level frameworks have been developed. These combine RVS screening with mechanical models for more robust evaluations. For example, Grant et al. (2007) [21] proposed a multi-level framework for school buildings, and Karatzetzou et al. (2023) [22] introduced an approach combining priority indices with fragility curves to assess a wider variety of building types, including precast and steel structures [23]. Despite these advancements, such approaches still face limitations in differentiating vulnerability within macro-classes.

This paper proposes a comprehensive prioritisation methodology for building stock evaluation, extending the work of Saler et al. on reinforced concrete schools [24-25]. The methodology incorporates various building types, including masonry, reinforced concrete, precast reinforced concrete, and steel, and integrates qualitative and quantitative assessments. The first level uses RVS forms adapted for different building types, while the second level employs simplified mechanical models for masonry and r.c. buildings and Single Degree of Freedom (SDOF) analysis for precast and steel structures. The methodology was applied to an industrial building portfolio in Italy, introducing new tools and combining results from both assessment levels into a final categorisation. As noted above, the proposed methodology enables the definition of prioritisation lists for interventions on the building stock. The strategic value of planning seismic retrofit interventions is widely acknowledged by the Civil Protection Department which is currently coordinating several research projects within the framework of the national risk assessment [26]; see, for instance, [27, 28].

2 METHODOLOGY

The methodology follows a two-level framework. The first level, or qualitative assessment, relies on reviewing original design documents and conducting on-site surveys to identify key seismic deficiencies. In this phase, the site's seismic hazard level is also considered to assign a qualitative vulnerability rating and define an initial prioritisation classification.

The second level, or quantitative assessment, involves seismic analysis using simplified structural models tailored to the building type. This assessment yields a safety index, offering a numerical measure of the building's seismic vulnerability and a second-level priority classification.

The integration of both levels enables a structured prioritisation approach, which enhances decision-making for risk mitigation in heterogeneous building stocks. Further details on the individual assessment levels and their combined application are provided in the following subsections. For a more detailed description of the methodology presented in this paper, refer to [29].

2.1 First-level assessment

The first-level analysis is conducted using checklist-based tools, which are specific to various construction technologies, to quickly identify seismic deficiencies. For masonry (M) and reinforced concrete (RC) ordinary buildings, the deficiency forms used in this study are derived and adapted from those issued by the Emilia-Romagna Region following the 2012 earthquake [30], as referenced in [24]. Since no specific deficiency forms were available for industrial buildings of other construction technologies (reinforced concrete I-RC and steel I-ST), these forms were developed in [29]. The deficiency grade by itself may offer limited deficiency/vulnerability levels (High, Medium and Low). The deficiency grade alone may have limited usefulness if it is not correlated with the specific seismic hazard of the construction site. To overcome this limitation, a risk metric was established using a decision tree approach (Figure 1), which incorporates both the deficiency grade and the seismic hazard level.

Seismic zones (PGA intervals)

Deficiency grade	**Z4** (<0,05g)	**Z3** (0,05-0,15g)	**Z2** (0,15-0,25g)	**Z1** (>0,25g)
High	C_I	C_I	D_I	E_I
Medium	B_I	C_I	C_I	D_I
Low	A_I	B_I	B_I	C_I

Figure 1: Priority classes for the first level, determined by deficiency grade and seismic hazard level.

2.2 Second-level assessment

The second level of assessment involves the use of various structural analyses based on the different construction technologies considered. A brief description of the different analyses is provided below, but for a comprehensive discussion, reference is made to the relevant publications. For masonry (M) and reinforced concrete (RC) technologies, two well-established methodologies have been adopted: VULNUS and FIRSTEP-RC, respectively. The VULNUS method, developed at the University of Padova [14,31], is widely employed for assessing the seismic fragility of masonry buildings, as demonstrated in studies such as Donà et al. (2020)

[32] and Saler et al. (2023) [24]. Regarding FIRSTEP-RC, the methodology has been developed at the Universities of Trieste and Udine [33,34]. The methodology has been successfully employed in the ASSESS project to appraise the seismic vulnerability of a school building stock in the Friuli-Venezia Giulia region in northeastern Italy [35,36].

In contrast, while established methodologies from the literature are used for the first two technologies (masonry and reinforced concrete), no similar methods for rapid seismic assessment were identified for industrial buildings made of reinforced concrete (I-RC) or steel (I-ST). Therefore, a new approach, based on the equivalent single degree of freedom (ESDOF) method, was proposed for these types of buildings. The choice to use the ESDOF method is based on the characteristics of industrial reinforced concrete and steel buildings. They are primarily single-storey structures, with floors and roofs that have low in-plane stiffness. This lack of diaphragm behaviour limits the ability to evenly distribute seismic forces across the vertical elements. As a result, the buildings exhibit a behaviour that can be simplified into independent "inverted pendulum" systems, where columns respond without significant interaction with the rest of the structure. For both types of industrial buildings analysed (I-RC and I-ST), the ESDOF method assesses two potential column failure mechanisms: combined compression-biaxial bending and shear failure. The corresponding safety index (α,b and α,s respectively) is determined for each mechanism. These indices are calculated by comparing the resisting moment (M_{Rd}) to the seismic moment (M_{Ed}) and the resisting shear (V_{Rd}) to the seismic shear (V_{Ed}), respectively. The seismic demand (M_{Ed}, V_{Ed}) is derived from the site-specific spectral acceleration (S_d), which is associated with the fundamental vibration period of the column, assuming an event with a return period of 475 years and a behaviour factor (q) of 1.5. Moreover, for I-RC buildings specifically, the analysis also considered the local failure mechanism resulting from support loss. Table 1 summarises the methodologies used for the different construction technologies and their corresponding bibliographic references. In addition, the safety factors are listed, both for global and local mechanisms, obtained from the different methodologies.

Building type	**Analysis approach**	**Safety factors (α_i)*** *global mechanisms*	*local mechanisms*
M	VULNUS [14,31]	$\alpha_{M,IP}$: in-plane shear of walls	$\alpha_{M,OOP}$: out-of-plane mechanisms of walls
RC	FIRSTEP-RC [33,34]	$\alpha_{RC,b}$: compression-biaxial bending of columns/walls $\alpha_{RC,s}$: shear of columns/walls	$\alpha_{RC,J}$: beam-column joint failure
I-RC (PRC/ LRC)	ESDOF [29]	$\alpha_{I-RC,b}$: compression-biaxial bending of columns $\alpha_{I-RC,s}$: shear of columns	$\alpha_{I-RC,\mu}$: beam-column support loss
I-ST	ESDOF [29]	$\alpha_{I-ST,b}$: compression-biaxial bending of columns $\alpha_{I-ST,s}$: shear of columns	-

Table 1: Essential information on the simplified analysis methods used and the associated failure mechanisms evaluated.

The outcome of the second-level assessment is an overall safety index for the building, which is defined as the minimum ratio of seismic capacity to demand, calculated using the different methodologies outlined above for each structural type. This index, combined with the qualitative method, leads to the establishment of five second-level priority classes (Table 2), ranging from A_{II} (lowest risk) to E_{II} (highest risk). The numerical thresholds for these classes were determined based on the Italian "Guidelines for the Seismic Risk Classification of Constructions" [37]. As previously mentioned, for a comprehensive and detailed discussion of the methodology, please refer to Gaspari et al. (2025) [29].

Second-level classes	Safety index
A_{II}	> 1.00
B_{II}	0.81 – 1.00
C_{II}	0.61 – 0.80
D_{II}	0.31 – 0.60
E_{II}	0 – 0.30

Table 2: Priority classes for the second level, determined by the building's overall safety index.

2.3 Combined seismic priority class

The two-level framework allows for the combination of the strengths of both methodologies while simultaneously mitigating their limitations. The second-level (quantitative) assessment method provides more precise and detailed results compared to the first-level (qualitative) method. However, the structural analysis procedures in the quantitative approach rely on simplified models and assumptions, which introduce the limitations discussed in the previous subsections. Conversely, while the qualitative (I-level) method offers less detailed results - relying on quick visual inspections to identify primary sources of seismic vulnerability - it can address aspects that the quantitative approach may overlook, thus complementing the overall assessment. The combination of both methodologies was carried out at the priority class level using the decision-tree approach depicted in Figure 2.

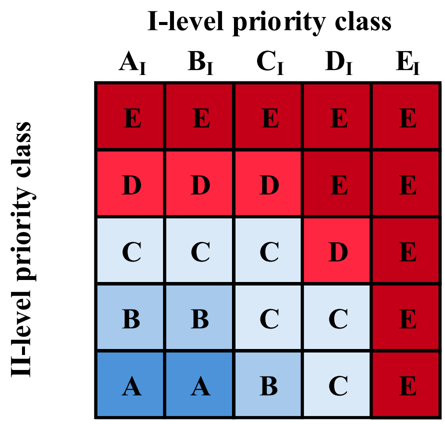

Figure 2: Combined priority class based on the priority classes of levels I and II.

3 CHARACTERISATION OF THE INDUSTRIAL BUILDING STOCK

This section presents an overview of the building stock inventory (Figure 3), which consists of 80 structural units (SUs). The majority of the buildings have reinforced concrete structures, categorized into three subgroups: ordinary reinforced concrete buildings (12 SUs), large-span reinforced concrete buildings (13 SUs), and precast concrete buildings (26 SUs). Additionally, the inventory includes 18 masonry buildings and 11 steel buildings.

An analysis of construction periods indicates that 95% of the structural units were built before 2001. Among these, 39% (31 SUs) were constructed between 1987 and 2001. Buildings erected prior to 1971 were designed solely for gravitational loads, as seismic regulations had not yet been introduced. From 1975 onward, standards evolved to account for horizontal forces. Construction techniques also changed significantly over time, with 58% of pre-1971 structural units consisting of load-bearing masonry. After 1971, precast reinforced concrete became increasingly common, ultimately becoming the dominant construction method after 2002. Between 1972 and 2001, reinforced concrete was used in 82% of the structural units, classified into ordinary, large-span, and precast reinforced concrete structures.

Regarding building function, most structures are designated for production activities (38 SUs), followed by office buildings (18 SUs), storage facilities (15 SUs), public service buildings (5 SUs), and residential buildings (4 SUs). Additional details on the building stock characterization can be found in Gaspari et al. (2025) [29].

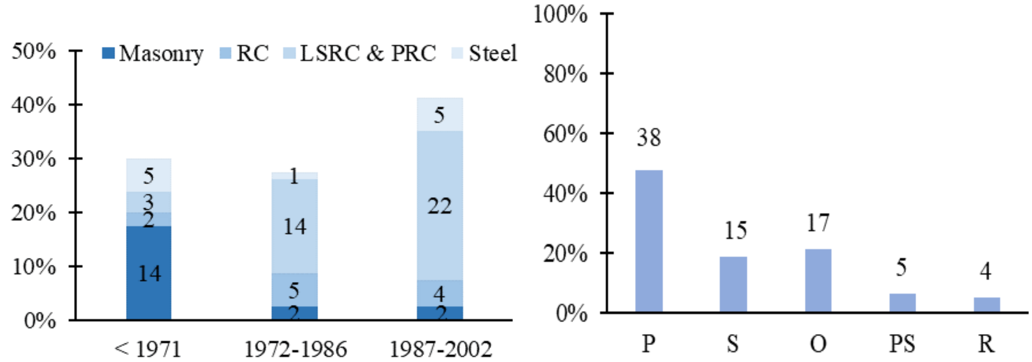

Figure 3: Distribution of construction technology and building use within the stock.

4 APPLICATION TO AN INDUSTRIAL BUILDING STOCK

The methodology introduced in Chapter 2 has been applied to the building stock described in Chapter 3. The following subsections present the results for the first level (Subsection 4.1), the second level (Subsection 4.2), and the combination of both levels (Subsection 4.3). For more detailed information and a comprehensive discussion of the results, please refer to Gaspari et al. (2025) [29].

4.1 First-level assessment

As mentioned in the previous chapters, the first-level assessment (qualitative assessment) is based on identifying building deficiencies with respect to seismic action. Figure 4 provides an application example for an industrial reinforced concrete (I-RC) building.

Figure 5 presents a summary of the key results obtained from applying the first-level seismic assessment to the analysed building stock. The results are sorted by construction technology (masonry M, reinforced concrete RC, industrial buildings made of reinforced concrete I-RC and steel I-ST). For the analysed stock, reinforced concrete structural units exhibit better classes compared to other technologies, with over 50% of the units in class B and the remainder in class C. Whereas, the steel technology shows the opposite trend, with 60% of the units in class D. Only one structural unit (of I-RC technology) falls into the lowest class (E), while no units are found in the highest class (A). For a more detailed discussion of the deficiencies identified in the analysed stock, please refer to Gaspari et al. (2025) [29].

SUs ID: ___________ DATE:__________

INSPECTOR:__________

DEFICIENCY FORM FOR EXPEDITIOUS SURVEY OF SEISMIC VULNERABILITY			
	I-RC STRUCTURAL UNITS		
	Deficiencies	**α**	**β**
1	Plan irregularity (very elongated shape in the presence of rigid ceiling, non-compact and/or non-symmetrical floor plan).		
2	Stiffness of the floors and/or their conformation (openings, etc.) not allowing distribution of seismic actions among resistant elements		×
3	Irregular distribution of masses and stiffnesses on floors with a surface area >80% of the covered area such as to result in an appreciable eccentricity between the centre of mass and the centre of stiffness (also taking into account the stiffness provided by the infill)		
4	Stair or lift cores eccentric in plan.		
5	Weak direction (frames in one direction only, insufficient number of walls…)		
6	Insufficient constraint in the foundation, considering the overall static scheme, against horizontal actions (poorly connected socket plinths)		
7	Vulnerability of supports in precast structures (brittle fractures, loss of support…)	×	
8	Presence of partial intermediate floors		
9	Strong elevation irregularity, with stiffness and/or strength increasing more than 100% at the successive above storey (accounting for infills stiffness contribution).		
10	Strong elevation irregularity, with stiffness and/or strength increasing more than 50% (and less than 100%) at the successive above storey (accounting for infills stiffness contribution).		
11	Evident and widespread vulnerability of infills towards out-of-plane overturning and column shear-sliding.		
12	Systematic presence of infills out of structural grid.		
13	Presence of slender columns and rigid and heavy slabs/beams.		
14	At each level, more than 30% of columns subjected to average compression stresses (seismic load combination) greater than 40% of design compression strength.		
15	At each level, more than 15% (and less than 30%) of columns subjected to average compression stresses (seismic load combination) greater than 40% of design compression strength.		
16	Evident susceptibility of more than 20% of vertical elements at each level to brittle fracture (short columns, discontinuous columns acting on beams/floors…)	×	
17	Evident susceptibility of more than 10% (and less than 20%) of vertical elements at each level to brittle fracture (short columns, discontinuous columns acting on beams/floors…)		
18	Severe and widespread deterioration of structural elements.		
19	Non-seismic joints or adherence among structural units (pounding).		×
20	Presence of vulnerable non-structural elements.		×
21	Presence of thrusting roofs for ≥ 50% of covered plan area.		
22	Presence of thrusting roofs for < 50% of covered plan area.		
	TOTAL	2	3

Please note: *If a cell is grey, it cannot be filled in. Deficiencies should only be recorded in white cells.*

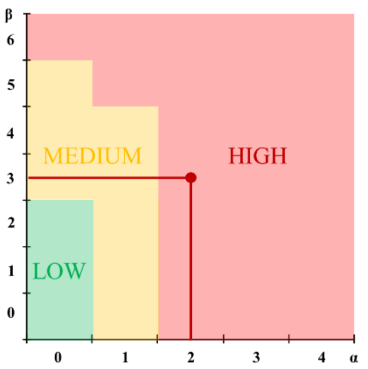

Figure 4: Assessment form for deficiencies in industrial reinforced concrete (I-RC) buildings technology, completed for the case study, along with supporting photos taken during the on-site inspection.

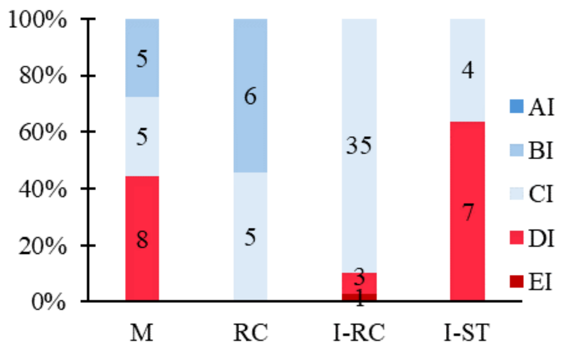

Figure 5: First Level assessments categorised by construction technology.

4.2 Second-level assessment

Figure 6 shows the distribution of the five assessment classes (from A to E) for the stock, sorted by construction technology. The M and I-RC technologies exhibit a distribution of classes similar to that observed in the first-level assessment. In contrast, for the RC and I-ST technologies, there is a reversal of the ratings. Specifically, the I-ST technology distributes its 11 structural units across the first two evaluation classes. The RC technology, on the other hand, has more than 60% of its structural units in class D. For a more detailed discussion of the collapse mechanisms observed in the analysed stock, both global and local, please refer to Gaspari et al. (2025) [29].

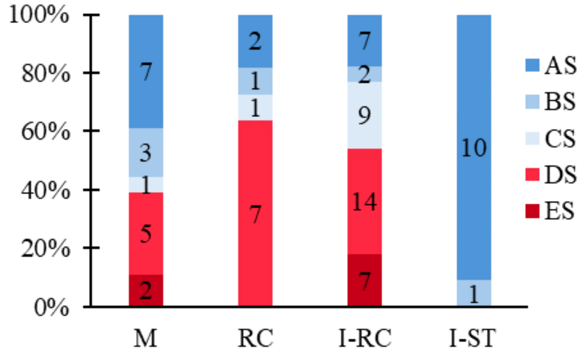

Figure 6: Second Level assessments categorised by construction technology.

4.3 Combined assessment

Figure 7 presents the results following the combination of the two analysis levels. For the considered stock, the I-ST technology shows the best seismic performance, with structural units falling between classes B and C. A total of 13 structural units are in the lowest class (E), with 7 from I-RC and 6 from M, respectively.

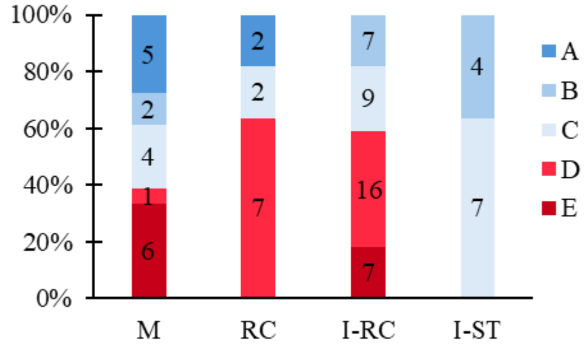

Figure 7: Combined assessments categorised by construction technology.

5 CONCLUSIONS

This study presents a comprehensive methodology for seismic risk assessment of heterogeneous building stocks, addressing gaps in current evaluation frameworks. By integrating qualitative deficiency-based assessments with simplified mechanical models, the proposed approach ensures a balanced and scalable evaluation suitable for various building types, including masonry, reinforced concrete (RC), precast RC, and steel structures. The methodology was applied to an industrial-oriented building stock, demonstrating its effectiveness in identifying key vulnerability factors. The two-level assessment approach provides more robust prioritisation by leveraging the strengths of both rapid screening and detailed mechanical models. It accounts for challenging-to-model vulnerabilities, such as pounding effects and non-structural weaknesses. The method also facilitates effective planning by distributing buildings across prioritisation categories (A-E). This approach supports informed decision-making and effective resource allocation for resilience planning at regional and national levels.

Future research could focus on refining the models, incorporating additional structural parameters, and validating the methodology on a wider range of building stocks. Extending the framework to include probabilistic approaches and economic impact analyses could further support decision-making and seismic risk mitigation strategies. Ultimately, the study advances seismic risk assessment by providing a practical, adaptable framework for informed decision-making, resource allocation, and resilience planning at regional and national levels.

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