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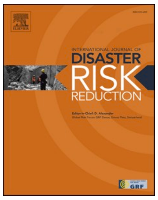

A new combined approach to prioritise seismic retrofit interventions on stocks of r.c. school buildings

Elisa Saler [a,*], Natalino Gattesco [b], Francesca da Porto [a]

[a] *Department of Geosciences, University of Padova, Via Gradenigo 6, 35131, Padova, Italy*
[b] *Department of Engineering and Architecture, University of Trieste, Piazzale Europa 1, 34127, Trieste, Italy*

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ABSTRACT

This paper presents a prioritisation procedure to rank reinforced concrete (r.c.) buildings that are part of a stock according to their seismic vulnerability, and to plan further verifications and retrofit interventions. The proposed approach is based on visual inspections, qualitative evaluation, and quantitative assessment. The qualitative evaluation is based on a new deficiency form, here presented, whereas the quantitative assessment is carried out through a simplified mechanical model, which provides a ratio of capacity to demand. This work thus proposes a combination of the qualitative and quantitative approaches aimed at prioritisation. In this way, specific limitations of each approach are overcome through the combination. The proposed procedure was applied to the r.c. school building asset managed by the municipality of Padova (Italy). After describing the main characteristics of the inspected stock, the paper discusses the most commonly observed vulnerability factors and the application of the procedure. The qualitative and quantitative approaches integrated each other quite well and showed a general good agreement.

1. Introduction

In seismic-prone country characterised by dated and vulnerable built heritage mitigation strategies must be planned and fulfilled, to enhance safety of people, reduce economic losses, and preserve cultural heritage and communities. Administrations and institutions in charge with critical assets (hospitals [1–3], schools [4], and transportation networks [5] among the others) are particularly involved in this process. Thus, efficient and cost-effective procedures are required to support decision-making to allocate limited funds.

In this context, a key role is played by school buildings, due to huge impact on communities in case of their collapse and loss of functionality. Indeed, school buildings are often dated and inadequate towards earthquakes [6]. The impact of seismic events on school assets on several country worldwide, as well as national plans put in place to enhance school safety, were presented by Alexandre et al. [4].

In the Italian context, earthquakes occurred in the last decades have demonstrated the high vulnerability of school buildings [7–10], as well as the impact of collapse and unusability of schools on communities [11]. In the aftermath of the Molise earthquake (2002), which caused the tragic collapse of a primary school in San Giuliano di Puglia (Campobasso, Italy), the Italian Government issued a Decree of paramount importance (OPCM n. 3274, 2003) [12], including a national plan for the seismic vulnerability assessment of relevant and strategic structures all over the country. The huge number of structures to be evaluated made this operation

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[*] Corresponding author.

E-mail addresses: elisa.saler@unipd.it (E. Saler), gattesco@units.it (N. Gattesco), francesca.daporto@unipd.it (F. da Porto).

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extremely complex and, after almost twenty years, it still requires efficient and cost-effective (also in terms of execution time) tools to be effectively planned. Prioritisation procedures are then needed for the allocation of resources (such as money, time, as well as technicians) to intervene on large building stocks [13]. In this framework, tools based on remote sensing and machine learning are rapidly growing; in the Italian context, some recent studies [14,15] attempted to exploit them for the seismic classification of buildings, based on satellite images, which is useful for a preliminary identification of the most vulnerable types.

Various priority-ranking procedures were proposed in the literature to evaluate stocks of school buildings. A multi-level procedure was proposed by Grant et al. [13] to assign priorities for the intervention, also providing the timescale for retrofit or demolition. The following year, the methodology was taken up and refined by Crowley et al. (2008) [16], on the basis of the collection of further data for school buildings in several regions of Italy. For analysis at national level, Borzi et al. in 2011 [17] proposed a multi-level methodology based on the simplified pushover-based model SP-BELA [18,19]. First, a quantitative mechanics-based assessment for macro-classes was carried out, and then the assessment was replicated considering specific features of each analysed building. These approaches, devised for large assets, did not provide an overall evaluation at all levels of the analysed stock, as it was expected that only a part of the analysed buildings would pass to the subsequent level of assessment. In addition, for r.c. buildings, the implemented mechanical models consider frame structural systems only.

Another multi-level approach to prioritise interventions on school buildings was developed by Grimaz et al. (2016) [20] in the framework of a regional project (for the Friuli-Venezia Giulia region, in North-East Italy) – i.e., the ASSESS project (2008–2011) [21]. The procedure provided a series of qualitative judgments to summarise the outcomes of the assessment; however, no detailed scoring was devised to sort buildings and thus prioritising interventions.

More recently, Gentile et al. [22] proposed a priority index for r.c. school buildings in Indonesia, based on fragility curves available in HAZUS [23], and on a performance modifier considering impacting characteristics of the analysed building and of the soil. Some vulnerability factors were not included in the performance modifiers, such as weak direction, flexible or poorly connected floors, and vulnerable non-structural elements.

Anelli el al. (2019) [24] proposed a methodology based on multicriteria decision-making to evaluate multiple pre- and post-earthquake mitigation policies, aimed at prioritising investments and enhancing resilience of schools. The evaluation was carried out through cost-benefit analysis in different scenarios. The main objective of this study was to set a framework for decision-making, by post-processing seismic assessment. Hence, it was proposed to carry out vulnerability evaluations through typological vulnerability functions, as further vulnerability assessment was out of the scope of the study.

Similarly, Jeswani et al. (2022) [25] proposed a multi-level framework for seismic risk assessment of building assets and evaluation of mitigation strategies, including casualties and downtime estimate. However, this approach was proposed for large assets of structures, and is therefore based on the definition of archetypes, not considering specific features of each building.

Other approaches were developed based on a rapid visual screening of risk factors for schools [26], general building assets [27,28] or for other type of stocks, such as hospitals [29]. Some of these studies attempted to calibrate a seismic risk index obtained from the rapid screening combined through fuzzy logic [30,31] or multi-criteria methods [32], or calibrated through empirical and numerical data [33]. These methods provide a score for each analysed building, with no mechanical evaluations of the global capacity.

Generally, the quantitative evaluation of a building safety is expressed as a ratio of capacity to demand, as provided by several technical codes around the world [34–36]. A recent study by Vona (2020) [37] proposed a probabilistic index expressing the exceedance probability of capacity, conditional to demand, for a required performance level. The proposed methodology thereby attempted to deal with uncertainties providing a probabilistic framework. To this end, it was based on of time-consuming nonlinear dynamic analyses applied to prototype buildings, being thus less suitable to catch peculiarities and complexity of structures part of a stock.

A number of studies have begun to investigate the behaviour of classes of school buildings, by focusing on typical local assets [38,39], or on some school building peculiarities. As an example, Ruggieri et al. (2022) [40] proposed a reduced-order multi-degree-of-freedom model for class-level assessment which allowed the plan irregularity to be accounted, also comparing results with other well-established methods for fragility assessment (i.e., SPO2FRAG [41] and multiple-stripe analysis [42]) [43]. Indeed, some specific features of school building (e.g., plan irregularities, large floor area, large floor span) shall be considered in class-level assessment, which is dealt with in current research for the Italian framework [44].

This paper provides a prioritisation procedure to sort school buildings part of an urban stock by their seismic vulnerability. This procedure has the aim of supporting local administrations and enterprises in charge with built stocks, which face the problem of allocating limited human resources and funds for seismic verification and retrofit of their buildings. The knowledge process of the building stock is comprised of on-site visual surveys and retrieval of original projects documentations. Then, the priority list is innovatively defined by combining a qualitative evaluation and a quantitative capacity/demand ratio resulting from a simplified mechanics-based model. The priority-ranking procedure was applied to reinforced concrete (r.c.) school buildings managed by the Municipality of Padova, in North-East Italy. Through this application, results of qualitative and quantitative approaches were compared and discussed, contributing to a deeper understanding of these tools and of the analysed building macro-class (i.e., r.c. school buildings in a recently classified seismic area).

2. Seismic vulnerability assessment procedure aimed at prioritisation

In this work, a novel expeditious procedure is proposed to rank buildings part of a stock, to prioritise the fulfilment of thorough seismic verification and then to manage a mitigation campaign through retrofit interventions. The proposed procedure is based on limited knowledge of buildings part of a stock, attained through on-site visual inspections and retrieval of documentation regarding original projects and later interventions. Visual inspections integrated information gathered from original documentations (Fig. 1). During on-site surveys, position of columns and frames was checked by observing cracks and thermophoresis phenomena. Great importance was given to the verification of structural elements geometry, as well as to the type and direction of floors. The efficiency of expansion joint towards seismic actions was judged based on their width, measured on site.

This methodology combines a qualitative classification, obtained through a survey form, and a quantitative index, calculated by applying a simplified mechanical method. The combination of two different methodologies allows the intrinsic trend of simplified approaches to neglect some vulnerability factors to be overcome. In addition, the quantitative method allows buildings within the same class (from qualitative assessment) to be sorted, thus obtaining a priority list manageable by administration in charge, who can allocate their limited funds for the most critical buildings.

For each building, the survey form provides a degree of deficiency (high, medium or low), which is evaluated by counting observed vulnerability factors. The degree of deficiency provides a first order of ranking of stock buildings, which are classified as having a high, medium, or low deficiency level. Then, a capacity/demand (C/D) ratio is calculated through a simplified mechanical model for each building. This ratio represents the second order of rating: buildings within the same deficiency level are sorted by increasing C/D ratio, starting from the most vulnerable.

Priority list is thereby defined according to these two orders of ranking. A scheme of the proposed procedure is given in Fig. 2.

This procedure was specifically devised to prioritise further analyses or interventions on building stocks subjected to an almost homogeneous seismic hazard (e.g., within a municipality). Caution is recommended when applying this approach to stock located in wider areas characterised by heterogeneous seismicity. In those cases, a greater weight should be indeed given to hazard, for instance by adding a previous order of ranking according to seismic demand, or by giving a greater importance to the C/D ratio. Further research is thus needed to better calibrate this procedure in case of heterogeneous hazard.

In this contribution, the proposed procedure was detailed for r.c. school buildings, also providing an application example, presented in Section 4.

2.1. Qualitative evaluation of degree of deficiency

Among on-site survey forms available in the literature, some were developed aimed at taxonomy definition, such as CARTIS [45], or damage observation and usability rating, such as Aedes [46]. One of the most acknowledged tools for expeditious vulnerability assessments is the GNDT form [47]. An updated version of the second level form for r.c. buildings was issued by the Marche Region (Italy) [48]. This form offers a fundamental reference for the listed vulnerability factors. However, the calculation of the vulnerability index, as the weighted sum of rating values assigned to vulnerability factors, is very well calibrated for the already listed factors, but little adjustable to different features of specific stocks. For instance, the GNDT form does not include the susceptibility of r.c. structures to pounding that, as presented later in this contribution, was commonly observed in the analysed school stock.

In this work, a tool for qualitative evaluation was selected based on its adaptability, in terms of ease of inclusion of different vulnerability factors. The qualitative rating is adapted from the Decree n. 14/2013 by Emilia-Romagna Region [49], which had the aim of managing the allocation of funds in the reconstruction phase following the Emilia Earthquake (2012), accounting for both observed damage and seismic vulnerability of hit buildings. The latter evaluation included a form to survey the deficiencies of inspected buildings.

The recalled procedure, developed and adopted after the above-mentioned earthquake, considered a list of 14 vulnerability factors for r.c. buildings. Those factors are classified either as severe (α) or moderate (β). Indeed, the severity of each deficiency was originally


Position of columns (cracks) *Position of frames (thermophoresis)* *Geometry of columns*


Type of floor (above ceilings) *One-way floors ((thermophoresis)* *Width of expansion joints*

Fig. 1. Information gathered through visual inspections.

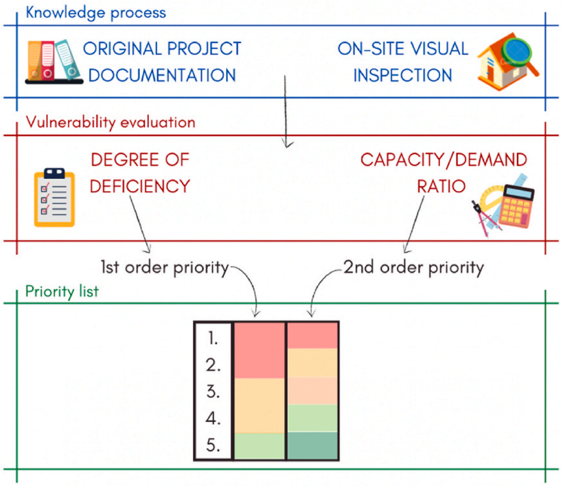


Fig. 2. Scheme of proposed prioritisation procedure.

defined in the form, and it does not depend on the surveyor judgement. In some cases, the same vulnerability factor is recalled twice in the form with different extent or intensity, to distinguish severe deficiencies from moderate deficiencies. A high level of deficiency is given by either a number of encountered severe (α) deficiencies equal or greater than two or a number of moderate (β) deficiencies equal or greater than six; a low level of deficiency is assigned in case of no α and at most three β; medium level is assigned in the other cases. Thus, combination of one α and five β formally does not represent a case of high level of deficiency, according to the Decree n. 14/2013 [49], despite being a more severe combination than six β. Un updated assignation rule is therefore proposed in this work, displayed in Fig. 3, attempting to set a more gradual classification, as well as to increase prominence of the critical combination of one α and five β deficiencies.

Original deficiency forms included in Decree n. 14/2013 [49] were already applied in a previous study to school buildings classified unusable after the Central Italy seismic sequence (2016) [50], when some limitations in the listed deficiencies, that is the need to consider other vulnerability factors, were first evidenced. Thus, we proposed a further update of the reference form for r.c. buildings of Decree n. 14/2013 [49], by adding some significant deficiencies that affect the seismic performance and are typical of the constructive systems of public buildings, such as schools. The following vulnerability factors were added:

- irregularity in plan (not approximately symmetrical and compact);
- eccentric position of stair and lift cores;
- weak direction (e.g., lateral resisting systems only along one direction);
- weak columns/strong beams (lack of capacity design);
- vulnerable non-structural elements (e.g., ceilings, chimneys, partitions);
- vulnerable precast structures (e.g., that can be subjected to loss of support, brittle failure of saddles).

Lastly, the modified deficiency form includes 17 vulnerability factors to be investigated, three of which are recalled twice, to

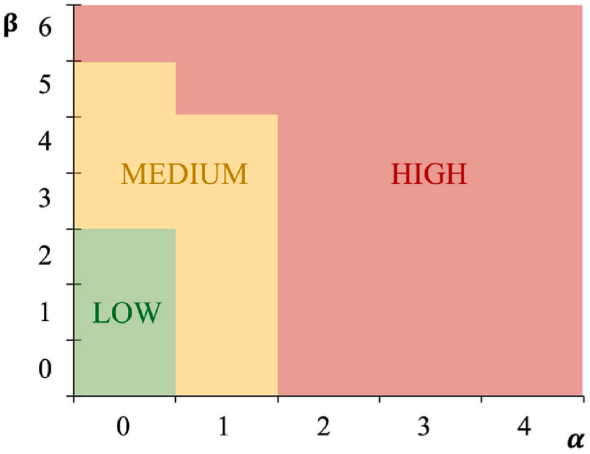


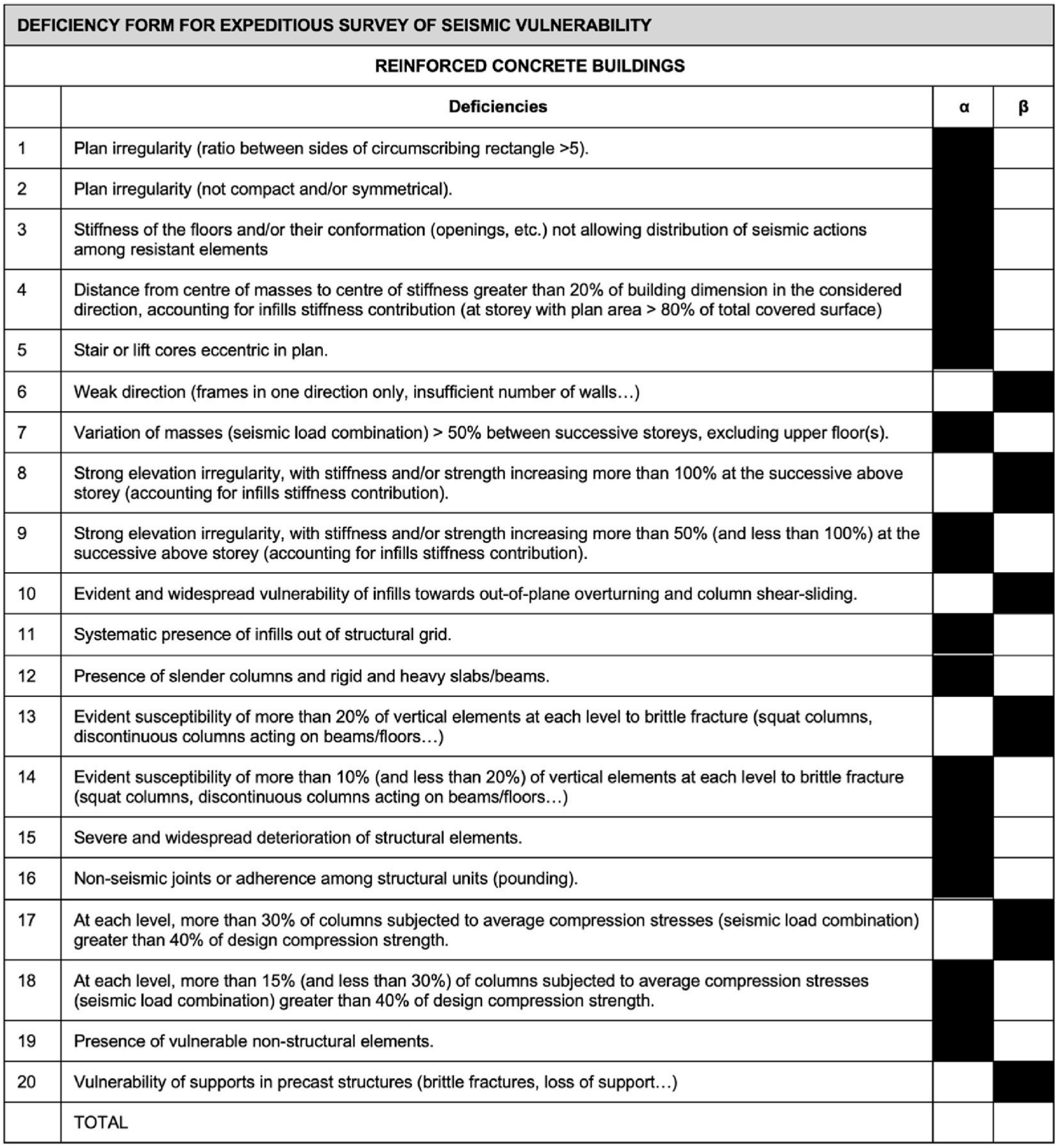
Fig. 3. Degree of deficiency according to number of α and β proposed in this work.

distinguish the severity of deficiency according to their extent, for a total of 20 deficiencies. Fig. 4 shows the updated form, where blank cells correspond to the assumed severity of each deficiency, which can be thereby marked when observed. Fig. 5 then illustrates the main deficiencies on a sketch of a complex school buildings.

Unlike other visual screening tools in the literature [29,51], the proposed deficiency form is solely based on vulnerability factors, including neither hazard aspects (e.g., seismicity level, soil type, slopes) nor exposure parameters (e.g., number of users), the latter according to stakeholders' preferences.

A more thorough comparison of the proposed form with Level 2 FEMA P-154 [51] rapid visual screening, accounting only for vulnerability factors, is proposed in Table 1. Multiple deficiencies in the proposed form for a vulnerability factor are indicated among brackets. Vulnerability factors addressed in the FEMA P-154 form are generally included in the proposed deficiency list. The latter does not account for the redundancy of structures, since factors improving the response are not considered, only deficiencies. Also, the case of other generalised irregularities is not included, as it was preferred to provide a comprehensive list of irregularity factors, reducing the subjectivity in filling in. Lastly, the presence of flat plates is not considered as specific vulnerability factor; however, the presence of heavy slabs on slender columns is included since it leads to a lack of capacity design.

The weights given by the compared forms also showed a general agreement; nonetheless some discrepancies can be observed and traced back to construction uses of reference areas (e.g., the high importance given to pounding effects in the US form).



DEFICIENCY FORM FOR EXPEDITIOUS SURVEY OF SEISMIC VULNERABILITY

REINFORCED CONCRETE BUILDINGS

	Deficiencies	**α**	**β**
1	Plan irregularity (ratio between sides of circumscribing rectangle >5).	■	
2	Plan irregularity (not compact and/or symmetrical).	■	
3	Stiffness of the floors and/or their conformation (openings, etc.) not allowing distribution of seismic actions among resistant elements	■	
4	Distance from centre of masses to centre of stiffness greater than 20% of building dimension in the considered direction, accounting for infills stiffness contribution (at storey with plan area > 80% of total covered surface)	■	
5	Stair or lift cores eccentric in plan.	■	
6	Weak direction (frames in one direction only, insufficient number of walls…)		■
7	Variation of masses (seismic load combination) > 50% between successive storeys, excluding upper floor(s).	■	
8	Strong elevation irregularity, with stiffness and/or strength increasing more than 100% at the successive above storey (accounting for infills stiffness contribution).		■
9	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).	■	
10	Evident and widespread vulnerability of infills towards out-of-plane overturning and column shear-sliding.		■
11	Systematic presence of infills out of structural grid.	■	
12	Presence of slender columns and rigid and heavy slabs/beams.	■	
13	Evident susceptibility of more than 20% of vertical elements at each level to brittle fracture (squat columns, discontinuous columns acting on beams/floors…)		■
14	Evident susceptibility of more than 10% (and less than 20%) of vertical elements at each level to brittle fracture (squat columns, discontinuous columns acting on beams/floors…)	■	
15	Severe and widespread deterioration of structural elements.	■	
16	Non-seismic joints or adherence among structural units (pounding).	■	
17	At each level, more than 30% of columns subjected to average compression stresses (seismic load combination) greater than 40% of design compression strength.		■
18	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.	■	
19	Presence of vulnerable non-structural elements.	■	
20	Vulnerability of supports in precast structures (brittle fractures, loss of support…)		■
	TOTAL		

Fig. 4. Deficiency form for r.c. buildings.

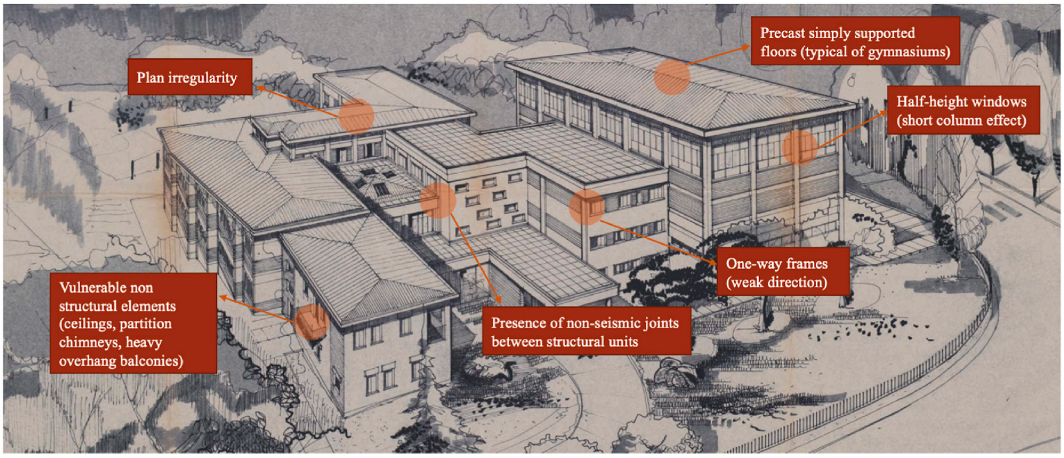


Fig. 5. A sketch of observed seismic deficiencies on a school building.

Table 1
Comparison of proposed deficiency form with FEMA P-154 [51].

Topic	FEMA P-154		Deficiency form		
Soft storey	✓	−0.9	✓		α
Weak storey	✓	−0.5	✓		β
Setback/discontinuous columns	✓	−0.3 ÷ 1	✓	(2)	α÷β*
Short column	✓	−0.5	✓	(3)	α÷β*
Split level	✓	−0.5	(for short column effect)	(2)	α÷β*
Plan irregularity	✓	−0.2 ÷ 0.7	✓	(4)	β
Other generalised irregularities	✓	−0.7	×		
Redundancy	✓	+0.3	×		
Weak direction	×		✓		α
Pounding	✓	−0.5 ÷ 1	✓		β
Flat plates as beams	✓	−0.4	×		
Flexible floors	×		✓		β
Loss of support (precast floors)	×		✓		α
Reduced ductility (lack of capacity design/column axial load)	×		✓		β
Non-structural elements	✓	–	✓	(2)	β
Deterioration	✓	–	✓		β

* depending on extent.

2.2. *Quantitative assessment through simplified mechanical model*

The ranking procedure then requires the application of a simplified mechanical model to the buildings of the analysed stock. The mechanical model shall be able to quantify the capacity of each structure in terms of a parameter that easily describes both capacity and demand, to calculate the capacity/demand ratio (I_S) and use that value to rank the buildings.

In this work, capacity from the simplified mechanical model and demand were expressed in terms of acceleration. For each building, capacity/demand ratios were calculated at Life Safety Limit State (LSLS) for each direction and for each structural unit. The minimum value of I_S was then used to rank buildings of the analysed stock. In addition, a seismic class (from A+ to F) was assigned to each building, based on I_S, according to the Italian Seismic Risk Classification (DM 63/2017 [52]). The intervals of I_S associated with seismic classes are shown in Table 2.

The capacity/demand ratio for each investigated building was assessed by applying the simplified FIRSTEP-RC method [53,54], developed in the framework of the above-mentioned ASSESS Project (2008–2011) [21].

Table 2
Definition of seismic classes based in I_s [52].

Seismic class	I_S
A+	I_S >100%
A	80%< I_S <100%
B	60%< I_S <80%
C	45%< I_S <60%
D	30%< I_S <45%
E	15%< I_S <30%
F	I_S <15%

Moreover, five gymnasium units were analysed based on a single-degree-of-freedom cantilever scheme.

The simplified FIRSTEP-RC method provides a capacity acceleration of the building, which is defined as the resistant acceleration (a_u), on soil A, of the weakest main direction. The total resistance base force is calculated through a linear equivalent analysis, conservatively assuming that the global capacity is reached as the first vertical structural element attains its ultimate limit state. It considers various collapse mechanisms that may occur: *i*) combined bending moment/axial load mechanism in r.c. walls and columns, *ii*) shear/sliding mechanism in r.c. walls and columns, *iii*) combined torsion and shear mechanism in beams in one-way frames, and *iv*) local collapse at beam-column joints. Analyses are carried out at ground floor, by applying a unitary storey force which is then distributed to each vertical structural element according to its stiffness and distance from centre of stiffness. Torsional effects due to eccentricity between centres of masses and stiffness are accounted. Thus, the portion of storey force (f_{ie}) on each vertical element is computed. For capacity evaluation, each vertical structural element is analysed separately, by defining its static scheme (in each main horizontal direction) based on type of element (either column or wall), constraint at base and at the top (the latter depending on type of beams), and number of storeys. In this phase, a reduced effective length of columns (e.g., due to half-height/ribbon windows) can be computed, as adopted in the current application when appropriate. A model scheme is provided in Fig. 6.

Then, the capacity force for each vertical element (F_{iu}) is computed as the minimum of shear capacities associated with the above-mentioned failure mechanisms. Details of rebars of vertical elements may be directly implemented, when available; otherwise, a simulated design procedure is carried out according to the Italian Code RD 2229/1939 [55]. The behaviour factor (q_i) related to the prevailing failure mechanism is thereby assigned to each vertical structural element.

For each main horizonal direction, the capacity force of the overall structure (FR) corresponds to the first vertical element attaining Life-Safety Limit State (LSLS) (Eq. (1)). The overall behaviour factor (q) is thereby computed according to equation (2). Capacity acceleration (au) is derived from capacity force (Eq. (3)), taking into account spectral (F0 = 2.5) and soil (S) amplification factors. Spectral amplification is thereby maximised, by assuming that the fundamental period of analysed structures corresponds to the spectral plateau. This simplification might be over-conservative for high-rise r.c. buildings, which generally have greater vibration periods. However, most schools have less than four storeys [56,57], thus the assumed simplification is reasonable for the analysed building type. For instance, in the inspected school stock analysed in this work (Section 3 and 4), no school building had more than three storeys. The total mass of the building (W/g) is also computed in the formulation.

$$F_R = \min\left(\frac{F_{iu}}{f_{ie}}\right) \tag{1}$$

$$q = \min_i\left(q_i \bullet \frac{F_{iu}}{F_R \bullet f_{ie}}\right) \tag{2}$$

$$a_u = \frac{F_R \cdot q \cdot g}{W \cdot S \cdot F_0} \tag{3}$$

The analysis approach (i.e., linear static) is compliant with ASCE 41 Tier 1 assessment [58]; however, the simplified model here adopted also considers the effective plan configuration of buildings (in terms of eccentricity of centre of masses and centra of stiffness, and thus of force distribution). This assumption is fundamental for building types that are often characterised by plan irregularity, as stated for school buildings [40].

Another mechanical approach adopted by regulations is SLaMA [59], included in NZSEE [36]. This simplified model, referred to displacement-based method, allows 2D r.c. frame and wall system to be analysed [60]. A recent refinement included the effects of infills [61,62]. However, torsional effects have yet been considered through a simplified calculation, and further developments are required to implement it for 3D complex structures [59,63].

The developed simplified method was validated though the comparison of results with numerical Finite Element models of school buildings case studies, as the example presented by Gattesco et al. (2012) [54].

Among the simplified mechanical model available in the literature [64], FIRSTEP-RC has the fundamental advantage of allowing the evaluation of r.c. frame, wall, and dual frame-wall buildings. Most of the methods found in the literature, in fact, although having the advantage of implementing non-linear analyses, are strictly limited to the analysis of frame buildings only [18,65,66]. Moreover,

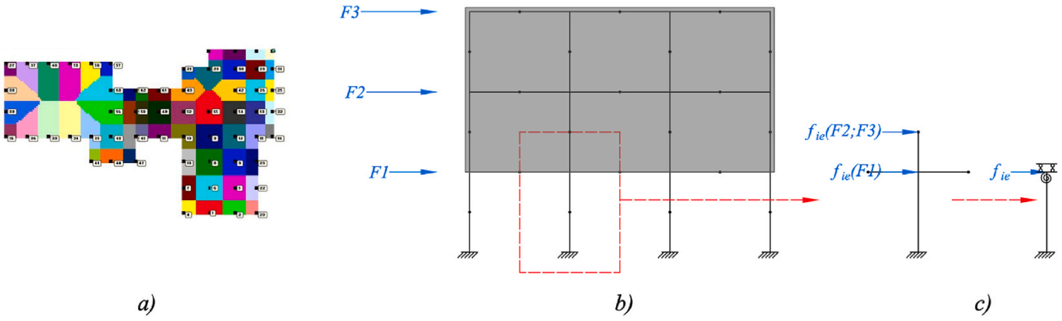


Fig. 6. FIRSTEP-RC schematisation: a) gravity load distributions; b) portal method scheme and c) actions and boundary conditions of the generic column.

FIRSTEP-RC was developed to evaluate the seismic vulnerability of specific buildings, accounting for more detailed features than approaches aimed at vulnerability estimate for macro-classes [18,67–69]. Therefore, despite requiring more input data to be applied in the analyses, it is expected to better catch each building singularities and to be suitable for evaluations at the level of building stocks. Indeed, the specific configuration of each building might play a crucial role in its seismic response and vulnerability, and thus in prioritisation [70]. Conversely, simplified methods based on a limited number of parameters were developed for generalised macro-classes of buildings, whose structural parameters are assumed either as deterministic or random variables on the basis of few known features (such as construction period). Hence, they are expected to be more suitable for analyses at a larger scale (e.g., regional or national). The used simplified methodology (FIRSTEP-RC) is based on the following assumptions, which must be kept in mind to better interpret results.

First, verification is carried out at ground floor, not considering possible irregular elevation arrangements, and beams are not verified (except against torsion generated by one-way frames). Structures with irregular plan shape could be analysed, as long as vertical structural elements form an orthogonal grid. Rigid diaphragms are assumed, thus flexible floors (e.g., simply supported precast floors) could not be adequately implemented. No interaction is considered among structural units.

For columns, formulations of shear resistance of r.c. elements without shear reinforcements [71,72] are assumed, due to generally weak contribution provided by stirrups. This formulation is conservative compared to cyclic shear resistance formulation available in Italian Code [73] and European Code (EC8- Part 3) [34]. However, cyclic shear resistance requires detailed information about reinforcements, thus it is less suitable for expeditious evaluations. In addition, computing shear resistance for r.c. elements without shear reinforcements penalises more recent structures, included in the stock assessment, since shear resistance considering adequate transverse reinforcements results generally greater.

Assumed static scheme corresponds to soft storey mechanism, with development of plastic hinges in columns and walls only at ground floors, neglecting other more favourable collapse mechanism, despite actual structural configuration. Lastly, capacity of the building is defined by the first vertical structural element to attain LSLS. Capacity assessment thus resulted conservative, as linear analyses tend to underestimate the global capacity of a structure with several degrees of hyperstaticity.

It shall be kept in mind that simplified methods tend to be conservative, and that consistency in terms of ranking structure is the main purpose of this procedure.

3. The r.c. school stock of padova

The proposed prioritisation procedure was devised and applied in the framework of a research agreement between the municipality of Padova, in North-East Italy, and the University of Padova. Padova is a relevant urban centre with an ancient historical centre, features that make it a representative provincial capital of its homogeneous territorial area, i.e., the Po Valley.

The Municipality manages various stock of public buildings, including many schools, thus needing support to prioritise seismic verifications, and retrofit interventions. Specifically, the municipality of Padova manages 99 educational complexes, including 105 school buildings. Of these, 25 are r.c. school buildings, representing 24% of the entire school stock (Fig. 7a). Despite the limited incidence of r.c. structures in the Padova stock, r.c. schools represent a rather interesting subset to be investigated. In fact, according to the Italian school building registry (ISBR) [46], which is comprised of almost 50,000 schools, r.c. school buildings are the larger subset in Italy (more than 16,000 structures, 33.5% of ISBR). Moreover, based on the same reference registry, most r.c. schools (91%) are designed without seismic provisions (i.e., for gravity loads only), as wide and densely populated areas of the country were only recently classified as seismic-prone.

In this section, typological and structural characteristics of this set of 25 r.c. school buildings are presented. As illustrated in Fig. 7b, in the analysed inventory, r.c. was initially used alongside traditional masonry systems (mixed structures), progressively becoming the most used construction technique in the most recent period (after 1976).

The analysed stock comprised educational institutes of various level of education, from nurseries to lower secondary schools (Fig. 8). Indeed, in Italy, higher secondary schools are managed by provinces. The stock includes other types of buildings related to education use, such as stand-alone gymnasiums. Reinforced concrete buildings were mainly built to accommodate lower secondary

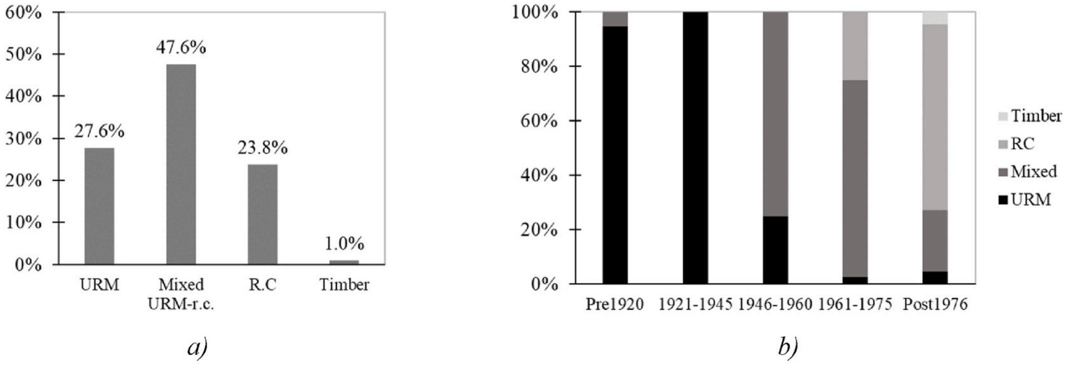


Fig. 7. Construction materials (a) and their evolution during periods (b) for schools in Padova.

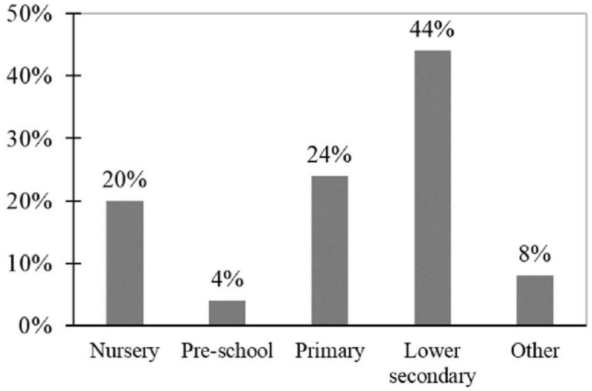
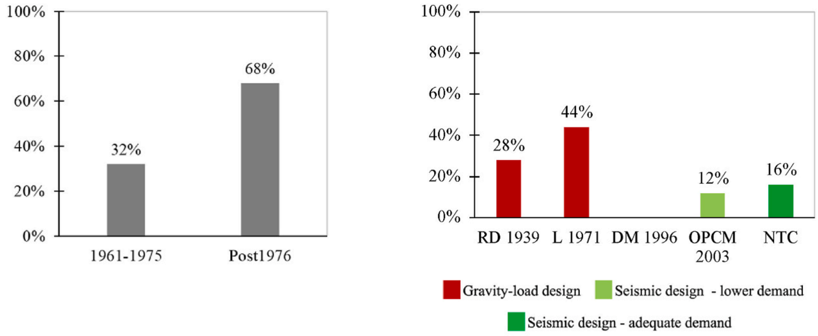


Fig. 8. Frequency distribution of educational level.

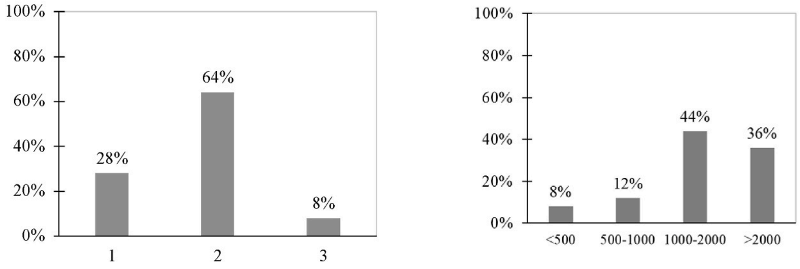
schools, which are typically larger and more complex, as for didactic purpose they might include gymnasiums, laboratories, auditoriums, and lecture halls. Surprisingly, a significant portion of r.c. schools in Padova are nurseries (20%). Actually, these structures are very recent, and the use of r.c. technologies is prevalent nowadays.

R.c. schools in Padova were built starting from 1961, with a peak in the most recent construction period, i.e., after 1976 (Fig. 9a). Each school was associated with Italian Code in force at the time of construction (Fig. 9b). R.c. buildings dated back before 1971 referred to the "*Regio Decreto*" (RD) n. 2229 of 1939 [55]. The construction of r.c. structures was then regulated by Law n.1086 of 1971 [74], in force over the entire country, and by Law n. 64 of 1974 [75], for seismic zones, which did not include the municipality of Padova at the time. Specific Decrees collecting the rules for construction were regularly updated until 1996, where novel Decrees for r.c. buildings were issued for the entire country [76], and specifically for seismic areas [77]. However, none of the schools of the inspected stock was built in the period 1996–2002. Moreover, with other Decrees the seismic prone areas were also updated. According to these norms, in Padova, buildings had been designed only for gravity loads until 2002. Then in 2003, after the 2002 Molise earthquake, Ordinance of the Prime Minister (OPCM 2003) [12] introduced mandatory seismic design in all the country, even though considering different levels of seismicity. Subsequently, novel technical codes for construction (NTC) [71,78] were issued, enhancing design of structures. Within the subset of r.c. schools of the Padova inventory, most buildings (72%) were designed considering only gravity loads. Fig. 9c and d shows frequencies of number of storeys and plan area, respectively. R.c. schools are mainly two-storey structures of large dimensions (over 1000 m^2).

Fig. 10a and b shows frequencies of types of lateral resisting systems observed, also disaggregating data according to construction



a) Construction period *b) Code in force at the time of construction*



c) Number of storeys *d) Covered plan area*

Fig. 9. Frequencies of typological parameters.

age. R.c. frames are the most common structural system, in particular with frames spanning in both main horizontal directions (44%).

One-way frames, which cause a weak direction, representing a seismic vulnerability, were used until 1975, then other systems were preferred.

Interesting data were collected regarding classes of concrete and reinforcing steel (Fig. 10c and d), by retrieving from municipal archives some test certificates carried out at the time of construction, or by assuming the material classes declared in the project documentation. Data were not available for a significant portion of buildings ("non defined" – ND); nevertheless, these data might be useful when analysing stock of coeval buildings in the same area, affected by lack of data. Concrete C20/25 was the most used, throughout ages. Only in recent times concrete classes C30/37 and C35/45 have been adopted in structural design and prescribed.

Reinforcing steel FeB44 was the most used steel class in both construction periods; it was introduced by the Decree of 1972 regarding r.c. and steel structures [79], thus its use was concentrated in last years of the period 1961–1975. Smooth rebars (classes AQ50 and FeB32) were found in project prescriptions for less than 10% of schools in the period 1961–1975, and for less than 5% of schools designed after 1976.

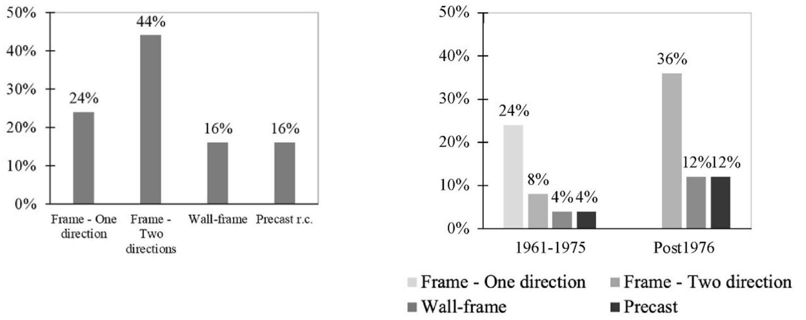
4. Results and discussion

4.1. Application of deficiency form on the analysed r.c. school stock

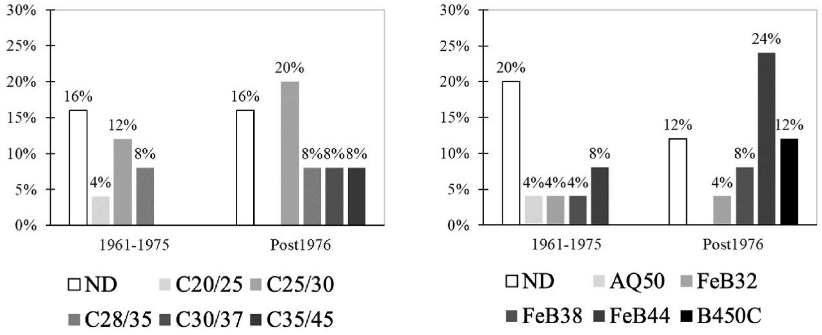
The updated deficiency form for r.c. buildings was applied to the above-described stock of school buildings and the results are hereafter presented.

Within the Padova inventory, r.c. schools (25 buildings) mainly showed a high deficiency level (60%), as illustrated in Fig. 11. This distribution can be better investigated by disaggregating the subset according to construction age (Fig. 12a). Distribution of deficiency levels within construction periods tended to improve during ages, as frequency of high degree of deficiencies decreased, until it disappeared after 2003. Vice versa low degree of deficiency was observed starting from 2003, and then it characterised all schools built after 2008. As mentioned before, no r.c. schools were built in the period 1996–2002. Furthermore, 2003 marked a turning point as year of seismic classification of the municipality of Padova. Distribution of deficiency level appeared evidently affected by design (either gravitational or seismic). Hence, seismic provisions deeply improved structural conception. The subset of gravity-load designed r.c. buildings (built between 1961 and 1995) was characterised by 83% of buildings with high and 17% with medium deficiency level.

A lower influence was observed for number of storeys (Fig. 13). Both two-storey and three-storey buildings showed a prevalence of high degree of deficiencies, while for single-storey buildings less vulnerability factors were generally observed. Indeed, some vulnerability factors regarding elevation irregularity between subsequent storey might affect only multi-storey buildings. In addition, based on the retrieved documentation, no higher level of care was observed in the design conceptualisation of multi-storey buildings. This might be explained by the low seismicity of the area (not considered in codes up to 2003), hence seismic effects (even qualitative)



a) Lateral resisting system *b) Structural systems given construction periods*



c) Concrete classes given construction periods *d) Steel classes given construction periods*

Fig. 10. Frequency of structural parameters and their evolution during construction periods.

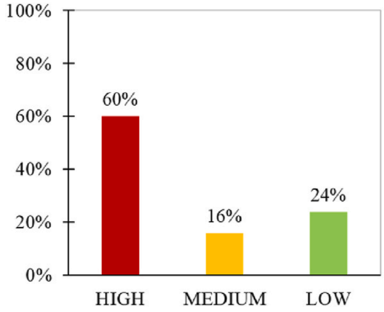


Fig. 11. Deficiency level for r.c. schools.

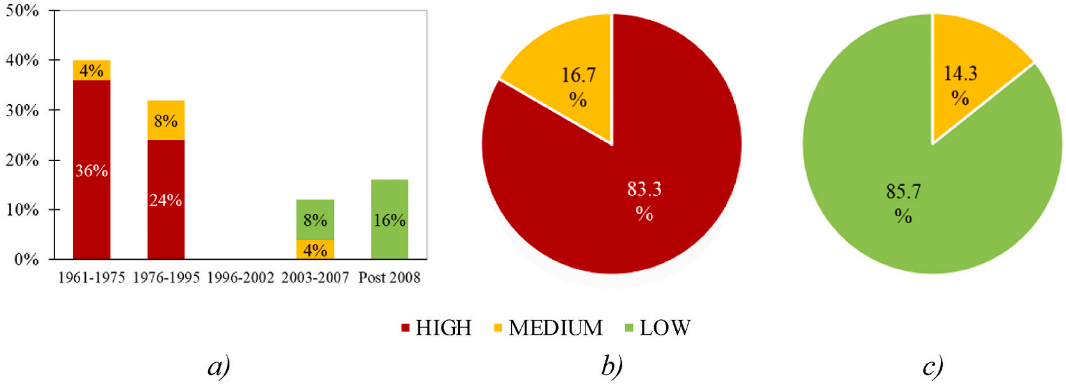


Fig. 12. Deficiency level for r.c. schools for construction period (a), and for subsets of gravitational (b) and seismic (c) buildings.

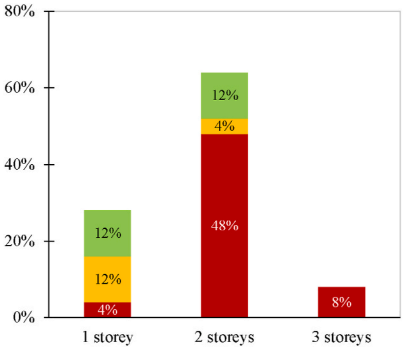


Fig. 13. Deficiency level for r.c. schools according to number of storeys.

were not considered by technicians. This finding can also be attributed to the lack of high-rise buildings within the stock (which could have been designed with the expected greater conservativeness).

Fig. 14 illustrates the frequency of observation of all deficiencies included in the updated form (which can be found in Fig. 4). The most frequently observed deficiencies are listed below, and illustrated in Fig. 15:

- Irregular, not compact, not symmetrical plan shape (Def. 2 – moderate).
- Flexible floors (generally precast simply supported floors) or configuration of openings in diaphragms affecting rigidity (Def. 3 – moderate).
- Vulnerability of infills towards overturning or (more commonly) generating short-column effect, due to ribbon or half-height windows (Def. 10 – severe).
- Non-seismic joints among structural units, with consequent susceptibility towards pounding (Def. 16 – moderate).
- Observed vulnerable non-structural elements, commonly high and heavy chimneys, cantilever roofs, heavy and deteriorated floor ceilings (Def. 19 – moderate).

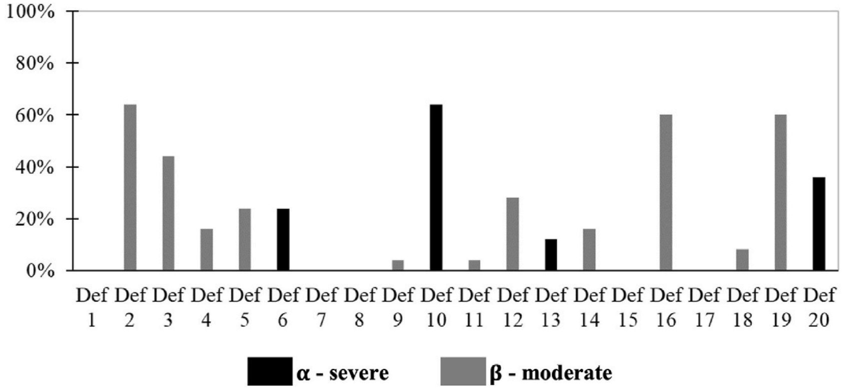


Fig. 14. Frequency of surveyed deficiencies for r.c. schools.

Fig. 15. Commonly observed deficiencies in the analysed stock.

- Vulnerable support in precast structures, susceptible to loss of support – lack of connections – and/or brittle fracture of saddles (Def. 20 – severe).

In particular, the vulnerability factors surveyed in most schools had a strong correlation with the educational function and the school architectural conception. Plan irregularity was very common, as well as presence of non-seismic joints or adherence among structural units, and presence of vulnerable non-structural elements.

The requirement of adequate natural lighting in classrooms led to widespread use of ribbon windows and half-height infills, which might increase column brittle failure occurrence. In addition, recent seismic events highlighted the importance of vulnerable non-structural elements, whose failure determined many unusable school buildings [10].

Table 3
Frequency of newly introduced deficiencies for r.c. schools.

N.	Deficiency	%
2	Plan irregularity (not compact, not symmetrical)	64%
5	Eccentric stair or lift cores	24%
6	Weak direction	24%
12	Weak column/strong beams	28%
19	Vulnerable non-structural elements	60%
20	Vulnerable support in precast structures	36%

For these vulnerability factors, suitable and commonly used retrofit solution might be: *i*) addition of novel external r.c. walls or bracing systems to counteract torsional effects due to plan irregularity; *ii*) strengthening towards shear failure for r.c. frames on façades that interact with half-height infills; *iii*) use of shock-transmitters to counteract pounding phenomena in case of non-seismic joints; *iv*) strengthening of partitions towards brittle failure and improvement of support systems of ceilings; and *v*) connection of precast floors (common in gymnasium buildings) to inhibit failure by loss of support.

Some vulnerability factors that were introduced by updating the deficiency form resulted significant within the analysed school set. Frequency of newly introduced deficiencies are presented in Table 3.

Plan irregularity, evaluated with reference to dynamically independent structural units, affected most r.c. schools, as well as the presence of vulnerable non-structural elements. Vulnerability related to simply supported precast roofs appeared rather widespread. It was commonly observed in lower secondary schools' gymnasiums and lecture halls. Eccentric cores, weak direction and weak column/strong beam configurations affected about a quarter of the evaluated subset. Thus, these newly introduced deficiencies resulted overall not negligible.

A major advantage of the proposed combined procedure is that the qualitative evaluation (using the presented updated form) can overcome the intrinsic simplifications of the mechanical approach, accounting for those vulnerability factors that are disregarded by the model. In this way, for example, irregular elevation arrangements, pounding susceptibility, and flexible floors (also in terms of loss of support) were thereby included in the final evaluation.

4.2. Application of mechanical model on the analysed r.c. school stock

The simplified mechanics-based model FIRSTEP-RC [54] was implemented for all r.c. school buildings within the Padova stock. Results in terms of I_S were conservative, being obtained through a simplified methodology based on linear analyses, where the global failure is associated with the first element to reach LSLS.

Fig. 16 shows results in terms of seismic classification of analysed buildings. Most of them were classified *F*, followed by *E*-classified structures. Also in this case, distribution of seismic classes can be better investigated by disaggregating the subset according to construction age and design conceptualisation (Fig. 17). Buildings classified *F* or *E* were all built before 1995, designed for gravity loads only. Some single-storey gravity-load designed buildings of earlier construction periods showed a better response. Seismically designed buildings (after 2003) showed a significantly reduced vulnerability, even though some recent buildings were penalised in the analysis due to assumption in evaluating shear capacity. For instance, the structure *D*-classified, built between 2003 and 2007 was particularly penalised by this fact. Increasing in seismic capacity of buildings over years is illustrated in Fig. 18, that compares capacity/demand ratios (I_S) for all analysed buildings sorted according to their construction year. In this figure, buildings were grouped together as gravity-load designed, seismically designed with seismic demand lower than nowadays, and seismically designed according to current standards. A generalised sudden increase in seismic capacity was observed, after the seismic classification of the municipality of Padova.

Lastly, Fig. 19 compares capacity/demand ratio distributions conditional to number of storeys. The least vulnerable seismic class ($A+$) was only obtained for single-storey buildings, while lower values of I_S were generally observed for multi-storey buildings.

4.3. Priority list and discussion

Results from evaluations of degree of deficiency and ratio of capacity to demand were combined to define the priority list for the r.c. school building stock, aimed at planning further verifications and retrofit interventions.

Simplified mechanical models might not include some vulnerability factors. For instance, the applied model, FIRSTEP-RC [54] evaluates the building capacity by analysing the ground floor, not always allowing implementation of irregular elevation arrangements. In addition, it always considers rigid diaphragms. Moreover, some vulnerability factors included in the deficiency form are hardly included in numerical simulations (e.g., susceptibility to loss of support, pounding, and vulnerable non-structural elements). Assuming that some of these factors should not be underrated, a greater weight in prioritisation was given to deficiency level, which represented the first order or ranking. Within the same degree of deficiency, schools were then ranked by vulnerability, according to capacity/demand ratio (I_S).

Priority list thereby obtained is displayed in Table 4, where typological features of analysed school buildings were also indicated.

Capacity to demand ratios were conservative; however, within the same degree of deficiencies, they are reasonably consistent in terms of sorting buildings to prioritisation.

A general good agreement was found among deficiency levels and seismic classes, suggesting consistency between implemented evaluations (qualitative and mechanical). Ranges of seismic classes identified within each deficiency level are compared in Fig. 20.

An overlap of seismic classes for low and medium deficiency levels was given by two anomalous cases (positions 20 and 21), whose specific features were less suitable to be analysed with the adopted mechanical method. Specifically, both school buildings were markedly penalised by the formulation for shear resistance used for columns: these schools are quite recent and have adequate stirrups, whose contribution is not computed in the implemented shear capacity model. Compared to other recent structures, penalisation for these cases was notable due to a greater weight of the floors, which determined higher seismic forces than in other schools.

Focusing on construction ages of ranked schools, results highlight the importance of design (gravitational or seismic) in defining vulnerability of each analysed buildings.

One unanticipated finding was that the ranking was not influenced by specific construction periods, as schools were not sorted consistently with decreasing age (not even roughly). This fact suggested that prioritisation according to typologies based on construction age might give erroneous results, by neglecting specific characteristics of each building that is part of a stock.

Regarding the influence of the number of storeys, single-storey buildings showed lower vulnerability according to both evaluations.

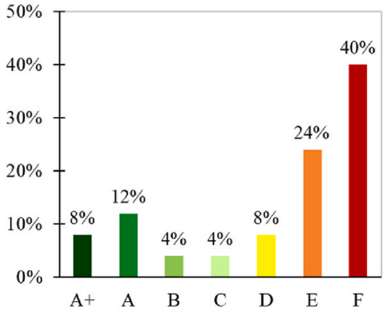


Fig. 16. Seismic classes for r.c. schools.

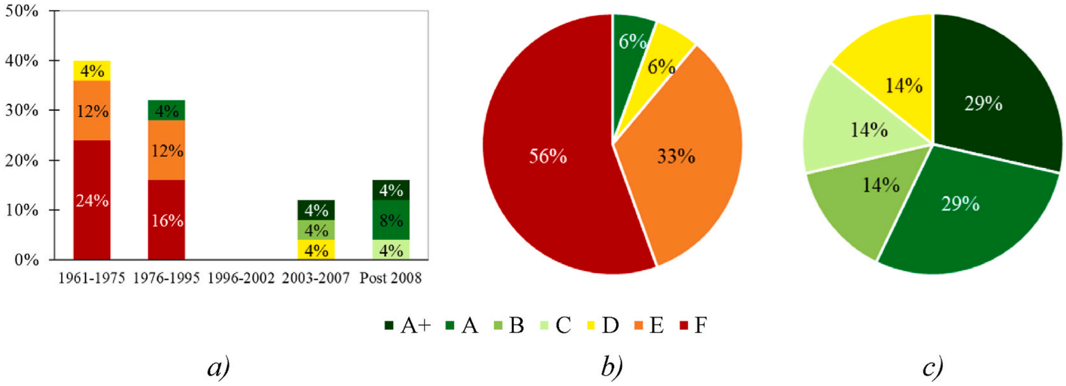


Fig. 17. Seismic class for r.c. schools for construction period (a), and for subsets of gravitational (b) and seismic (c) buildings.

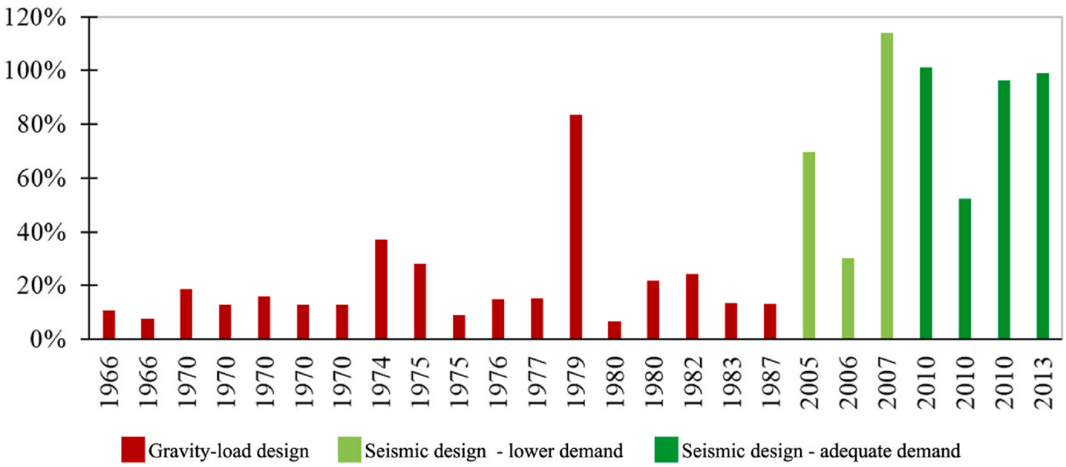


Fig. 18. Trend of I_S ratio according to construction year of r.c. schools.

A preliminary comparison of these findings with more refined finite element models was carried out. Two school buildings were selected (position 2 and 12) from the investigated stock and modelled by using the software MidasGen [80]. Infill panels were included through macro-modelling. Linear dynamic analyses were implemented, and verifications were carried out for vertical elements, to provide a consistent comparison with the computation of FIRSTEP-RC. Results are summarised in Fig. 21.

Both schools showed a level of safety lower than the minimum safety level inferable from the Italian code for schools (60%), based on the minimum level required for seismic improvement [73]. Thus, they appeared in need for a retrofit intervention (in line with the high deficiency level obtained). The verification values obtained from FEM reflect the order of priority found with FIRSTEP-RC.

First findings were thus encouraging. Further refined models are needed to enlarge this comparison, also considering non-linear analysis.

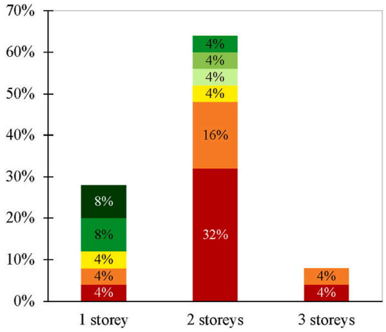


Fig. 19. Seismic class for r.c. schools for number of storeys.

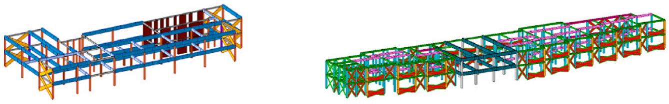
Table 4
Priority list of r.c. school stock.

	Level of education	Age	N. of storeys	Deficiency level	I_S	Seismic class
1	Lower secondary school	1976-1986	2	HIGH	6.7%	F
2	Primary school	1961-1975	2	HIGH	7.8%	F
3	Lower secondary school	1961-1975	2	HIGH	9.2%	F
4	Nursery	1961-1975	2	HIGH	10.6%	F
5	Lower secondary school	1961-1975	2	HIGH	12.9%	F
6	Gymnasium	1961-1975	1	HIGH	12.9%	F
7	Lower secondary school	1961-1975	2	HIGH	12.9%	F
8	Lower secondary school	1987-1995	2	HIGH	13.4%	F
9	Lower secondary school	1976-1986	2	HIGH	13.6%	F
10	Primary school	1976-1986	3	HIGH	14.8%	F
11	Lower secondary school	1976-1986	2	HIGH	15.2%	E
12	Lower secondary school	1961-1975	2	HIGH	15.9%	E
13	Primary school	1961-1975	3	HIGH	18.8%	E
14	Lower secondary school	1976-1986	2	HIGH	22.0%	E
15	Lower secondary school	1961-1975	2	HIGH	28.2%	E
16	Nursery	1976-1986	1	MEDIUM	24.1%	E
17	Gymnasium	1961-1975	1	MEDIUM	37.2%	D
18	Primary school	2003-2007	2	MEDIUM	69.8%	B
19	Pre-school	1976-1986	1	MEDIUM	83.6%	A
20	Lower secondary school	2003-2007	2	LOW	30.2%	D
21	Primary school	Post 2008	2	LOW	52.4%	C
22	Nursery	Post 2008	1	LOW	96.3%	A
23	Primary school	Post 2008	2	LOW	99.2%	A
24	Nursery	Post 2008	1	LOW	101.1%	A+
25	Nursery	2003-2007	1	LOW	114.1%	A+

Fig. 20. Ranges of variation of seismic class within degree of deficiency.

In future investigations, results of the proposed procedure can be used as input for selecting optimal retrofit solutions, using multi-criteria decision making (MCDM) approaches. A previous study [81] indeed showed that simplified methods can be effectively applied as input parameters of these approaches (also integrating the influence of insurance coverage [82]).

Certainly, nowadays seismic retrofit requires an effective integration with energy aspects [83,84]. The priority list provided by the



FEM	$I_S = 8\%$	$I_S = 16\%$
FIRSTEP-RC	$I_S = 44\%$	$I_S = 53\%$

Fig. 21. Results of linear dynamic analysis on FE models for two schools.

current methodology represent a useful tool to integrate seismic evaluations with indicators of energetic performance through MCDM approaches [85] Indeed, various parameters from the proposed procedure can represent criteria for MCDM aimed at integrated prioritisation or selection of optimal retrofit: not only does the list provide the position of each school as criterium, but also a qualitative judgement (level of deficiencies) and a quantitative parameter (capacity/demand ratio).

5. Conclusions

This paper presents an expeditious procedure to define priority lists for r.c. buildings part of a stock, based on visual inspections and retrieval of original project documentations. It combines a qualitative classification, evaluated through a deficiency form, and a ratio of capacity to demand evaluated by applying a simplified mechanical model. Deficiency level (high, medium, or low) represents the first order of prioritisation. Within the same deficiency level, buildings are sorted by increasing capacity/demand index. Priority list is thereby defined.

Based on the experience gained from in-situ surveys, a novel and updated deficiency form was presented for r.c. buildings. The proposed procedure was applied to 25 r.c. facilities within a stock of school buildings, from nurseries to lower secondary schools, whose typological and structural characteristics have been extensively presented in this paper. Only seven r.c. schools were designed according to seismic provisions, while other buildings were design with reference to gravitational actions only.

For the analysed stock, most of the newly introduced deficiencies in the r.c. survey form showed a significant frequency of observation and relevance. Several vulnerability factors were surveyed in the great majority of evaluated buildings, thus suggesting that they may characterise structures with educational function: plan irregularity, presence of non-seismic joints among structural units, vulnerable non-structural elements.

By carrying out simplified mechanical analyses, prioritisation of r.c. schools appeared to be mainly affected by design conception (either gravitational or seismic) and not directly by construction ages. This fact suggested that prioritisation according to building taxonomy (specifically construction period) might neglect significant building features, yielding to non-accurate priority lists.

Therefore, combined procedure allows specific limitations of each methodology to be overcome. Specifically, qualitative classifications may result in a great number of structures within one class, generally the worst class for all dated buildings. In this case, the number of buildings needing interventions, according to the classification, might be not reasonably manageable by the administration in charge. The quantitative evaluation thus provides a detailed priority list, fundamental to support decision-making on further verification and intervention planning. On the other hand, simplified models tend to neglect some vulnerability factors, which are included in the current approach thanks to the preceding qualitative assessment.

Although the surveyed r.c. building stock is limited in terms of number of structures, and is located in a geographically narrow area, ongoing analyses have demonstrated that the analysed stock is characterised by features that are recurring for school buildings at a larger (national) scale. In addition, by applying the proposed procedure to the selected stock, a general good agreement was observed in qualitative and mechanical evaluations. Further works on refined finite element models of schools of the analysed stock would be worthwhile, in order to compare results here presented.

This research also opens up the evaluation of the effects of interventions on stocks of structures, considering their effectiveness in improving both deficiencies and seismic classes.

Therefore, despite further research is needed to better calibrate the proposed procedure, for example to consider building assets subjected to heterogeneous seismic hazard, the proposed combined approach appears a quite robust, very practical, and promising tool to support administrations and institutions in charge of decision-making to define efficient mitigation strategies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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