A priority-ranking procedure to assess seismic vulnerability of school buildings at territorial scale

Elisa Saler[a], Pietro Carpanese[b], Valentina Pernechele[b], Francesca da Porto[b]
[a] *Dipartimento di Ingegneria Civile, Ambientale e Meccanica, Università di Trento, Via Mesiano 77, 38123 Trento, Italy*
[b] *Dipartimento di Geoscienze, Università di Padova, Via Gradenigo 6, 35131 Padova, Italy*

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ABSTRACT

Italian school heritage is largely composed by dated buildings, which have clearly shown high vulnerability during recent earthquakes. The evaluation of the seismic vulnerability of school buildings has a crucial role in the mitigation of earthquake impact due to the consequences associated with their collapse. For this reason, after the tragic collapse of a school building during the 2002 Molise earthquake, an important national plan has been set up with the aim of assessing and mitigating risk for relevant and strategic structures. Hence the need to find cost-effective and efficient strategies to plan vulnerability reduction and to devise priority lists for the interventions in order to help local authorities to allocate limited funds. In this framework of resources optimisation, this study aims to implement a procedure to sort the buildings by vulnerability to budget deeper investigations and retrofitting and to devise mid-term and long-term mitigation strategies. In particular for reinforced concrete (RC) buildings, high vulnerability is due to many aspects, mostly related to the age of the buildings, the poor quality of concrete and the gravity load design in areas mistakenly considered as non-seismic zones until recent times. The latter aspect leads to inadequate construction details, a lack of ductility and capacity design and irregular configurations determining global torsional effects. The vulnerability assessment is carried out considering both a qualitative degree of deficiencies (low, middle, high) and a quantitative capacity/demand ratio calculated through simplified methods from literature. The deficiencies taken into account are related to plan and elevation irregularity, poor seismic details, possible brittle fractures and vulnerability of non-structural elements. This procedure has been applied to reinforced concrete school buildings owned by the Municipality of Padova, from nurseries to lower secondary schools.

1 INTRODUCTION

Seismic vulnerability assessment represents one of the main tasks when evaluating seismic risk, especially in a country with a historical building stock and high seismicity like Italy. Even greater attention must be paid when examining the vulnerability of strategic buildings, such as schools. In our country, more than 60% of the school buildings were built between 1945 and 1980, i.e. after World War II, when reinforced concrete building stock increased exponentially (Clementi et al. 2015).

The Italian seismic events of this century (e.g. Molise 2002, L'Aquila 2009, Emilia 2012 and Central Italy 2016) have highlighted the high seismic vulnerability of the Italian existing RC buildings, mainly due to their age, low construction and maintenance standards, and their own design, which often did not take into consideration the correct seismicity of the area. As a matter of fact, some earthquake-prone areas had been mistakenly considered as non-seismic zones, many of the municipalities had not been classified yet and their structures had been built without seismic provisions (Augenti et al. 2004).

In addition, with regard to schools in Italy, this type of buildings is characterised by eccentricities and irregularities in plan configuration, large atriums with double heights, uneven distributions of heavy infills, and soft storeys; all these aspects lead to negative effects on both local and global structural behaviour, with possible torsional effects. Furthermore, most of the schools built without seismic criteria were altered during the following decades, and those modifications frequently increased their seismic vulnerability.

After the 2002 Molise (Italy) earthquake, Italian Government started a mitigation policy on the basis of the Ordinance of the President of the Ministers’ Council (OPCM n. 3274, 2003). More specifically, a national plan was devised with the aim of assessing and mitigating the risk of those buildings (in particular critical buildings, including schools) designed without earthquake resistant criteria. For this purpose, it is nowadays crucial to implement a procedure to sort the buildings by vulnerability, in order to prioritise retrofitting and seismic mitigation strategies.

This paper proposes a procedure to sort the buildings by seismic vulnerability to provide a decision-making support to local administrations in budgeting deeper investigations and retrofitting. The procedure implemented both an analytical qualitative assessment and a mechanical simplified model combining their results to rank the school buildings of the analysed stock.

2 STATE OF ART

2.1 *Macro-scale seismic vulnerability assessment*

Priority-ranking procedures that identify the school buildings with highest risk based on filters of increasing detail have been recently proposed. As an example, the method developed by Crowley et al. (2008) measures the difference between the design forces defined for the building site and an estimation of the level of seismic resistance which was required at the time of design, then calculating lateral strengths following a displacement-based methodology. This framework proposes a priority list for seismic interventions on school buildings in Italy, which are ranked in order of decreasing risk rating.

The framework proposed by Anelli et al. (2019), suggests innovative metrics to measure the resilience of school systems, considering engineering, socio-economic and political aspects. This method also emphasises the importance of an easy understanding of the framework adopted, in order to let institutions and politicians make conscious choices about different mitigation strategies.

Another method used for prioritising retrofit interventions has been developed in the framework of the ASSESS project (Franceschinis, 2012; Grimaz et al., 2016). This framework originally aimed at assessing the seismic risk of school buildings in the Friuli Venezia Giulia region; also, it identifies the possible actions for improving seismic safety, making economic evaluations and defining intervention priorities for reducing seismic risk. Even in this case, the method aims to help public administrators in the development and management of strategies for seismic risk mitigation of schools, considering not only building vulnerability but also all the other aspects related to safety; by means of this method, an estimate of the financial resources necessary for the implementation of retrofit interventions can be identified as well (Grimaz et al. 2011).

During the course of the ASSESS Project (2008-2011) a new simplified mechanical procedure called “FIRSTEP-RC” has been developed to assess the seismic resistance of reinforced concrete structures taking into account the various types of failures that may occur to the vertical elements: shear collapse, combined flexure and axial force collapse, local collapses. The seismic safety index of the structure (I_s) is defined as the ratio between the resisting acceleration in the weaker direction and the seismic acceleration expected (Gattesco et al. 2012).

2.2 *Expedition on site forms*

Various forms useful for collecting data and carrying out expeditious vulnerability assessment are available in literature.

The CARTIS form (*CARatterizzazione TIpologico-Strutturale dei comparti urbani costituiti da edifici ordinari*) is a tool for improving building taxonomy and the knowledge of its territorial distribution at national level in Italy (Zuccaro et al. 2015). It is meant to identify the main ordinary building macro-typologies for homogeneous areas in different Italian municipalities, in order to obtain a statistical distribution in terms of construction periods and structural typologies. As already mentioned, the

CARTIS survey refers only to ordinary buildings (mainly residential), however many of its fields can be applied to school buildings.

Another useful tool widely used when making safety evaluations on buildings is the G.N.D.T. form (Benedetti and Petrini 1984, Regione Toscana 2004). This survey allows the sensing of building exposure and vulnerability, and it features two levels of detail: the First Level and the Second Level. While the First Level form only requires basic geometric and typological information (as well as the possible damage level), the Second Level form investigates more deeply geometric and constructive parameters and it contains specific fields for masonry buildings and reinforced concrete buildings.

When specifically assessing post-earthquake damage, the main tool is the AeDES form (Baggio et al., 2000) which evaluates the damage based on its intensity and its extension for each structural and non-structural element of the building.

The Ordinanza n. 14/2013 by Emilia Romagna Region aims to give a qualitative vulnerability assessment (low, moderate and high) for the buildings damaged by the 2012 Emilia earthquake. The vulnerability level is given by the combination of a “degree of deficiencies” with a capacity/demand ratio in terms of acceleration at the Life Safety Limit State (LSLS). The degree of deficiency is calculated counting the present vulnerability factors (classified as severe-alpha or moderate-beta), listed in the form for masonry and reinforced concrete buildings respectively. The degree of deficiency proposed by the Ordinanza n.14/2013 was used by ReLUIS consortium during technical surveys of school buildings in the aftermath of the 2016 Central Italy earthquake, supporting the Department of Civil Protection and local administrations in the decision process between retrofitting and relocation for school buildings classified unsafe, i.e. outcome E of the AeDES form (Calderini et al. 2017, Di Ludovico et al. 2017; Di Ludovico et al. 2018). It has been observed that, for masonry buildings, the Ordinanza n.14/2013, does not evaluate factors such as irregularities in plan and elevation, presence of static forces, slenderness of vertical structures and vulnerability of non-structural elements. It is hence important that those parameters are included in the form (Cescatti et al. 2017).

3 SIMPLIFIED PROCEDURE FOR SEISMIC VULNERABILITY ASSESSMENT

The proposed procedure is a combination of a qualitative analytical method and a quantitative simplified mechanical numerical method in order to define a priority list for interventions. The combination of two methods allows overriding the intrinsic tendency of simplified methods to neglect some factors which affected seismic vulnerability.

3.1 Analytical method

The proposed analytical method is based on the deficiency form of the above-mentioned Ordinanza n. 14/2013, improved by the addition of some deficiencies for RC buildings in order to take into account other factors affecting seismic performance, in particular:

- Plan irregularity (not approximately symmetrical and compact).
- Stair and lift cores eccentric with respect to the plan.
- Weak direction (e.g. unidirectional frames, insufficient walls).
- Weak columns/strong and heavy beams.
- Vulnerable non-structural elements (e.g. chimneys).
- Precast structure vulnerabilities (e.g. support loss, brittle fracture of the saddles).

Thus, the modified deficiency form for RC buildings includes twenty vulnerability factors to be investigated. A high degree of deficiency is defined by a number of alpha deficiencies greater than 2 or number of beta greater than 6 or equivalent (1 alpha and 5 beta lead to a high degree of deficiency); a low degree of deficiency is defined by no alpha and at most 3 beta; medium degree in the other cases.

3.2 Mechanical numerical method

The definition of a priority list requires a quantification of the seismic capacity of each building to rank all the elements of the stock.

In order to evaluate the resistance acceleration of RC buildings, the simplified mechanical procedure “FIRSTEP-RC” (Gattesco et al. 2012) has been applied. The simplified procedure calculates the resistance base shear and behaviour factor with a linear analysis, defining global capacity as the first element reaches its ultimate limit state, providing conservative results in terms of overall structural response. Finally, the procedure provides resistance acceleration (Equation 1), scaled to consider soil effects, for each direction and structural unit of the analysed building.

$$a_u = \frac{F_R \cdot q \cdot g}{W \cdot S \cdot F_0} \qquad (1)$$

The most important simplification introduced is the analysis of each building with reference to the resistant elements at the ground floor only. Thus, some vulnerability factors linked to the elevation arrangement cannot be taken into account, i.e. elevation irregularity, soft-storey mechanism and pounding. Hence the need to compare results from analytical and mechanical analyses to have a more complete view of the stock vulnerability.

“FIRSTEP-RC” cannot implement flexible floors. Therefore, a simplified calculation assessment has been applied to the cases of flexible and semi-rigid diaphragms, i.e. simply supported precast floors largely used for gymnasium roofs. In this case, columns are modelled as cantilever with lumped mass on top. Then a linear analysis is performed on a single-dof scheme.

Results from mechanical models have been summarised in a capacity/demand index (Is), at LSLS, which is the minimum for each direction and each structural unit composing the school building. Consistently with Italian Seismic Risk Classification (DM 63/2017), seismic classes from A+ to F have been assigned to each building, based on the capacity/demand ratio (Table 1).

Table 1. Definition of Seismic Classes based on C/D index.

Class	C/D index
A+	Is>100%
A	80%< Is <100%
B	60%< Is <80%
C	45%< Is <60%
D	30%< Is <45%
E	15%< Is <30%
F	Is <15%

4 APPLICATION TO A RC SCHOOL BUILDING STOCK

With the aim of assessing the school building stock owned by the municipality of Padova, 96 schools were surveyed, from nurseries to lower secondary schools, plus two buildings relevant to educational use, including masonry, mixed masonry-RC and RC buildings (Figure 1). In this framework of macro-scale assessment, the proposed methodology has already been applied to the 22 reinforced concrete buildings included in the stock.

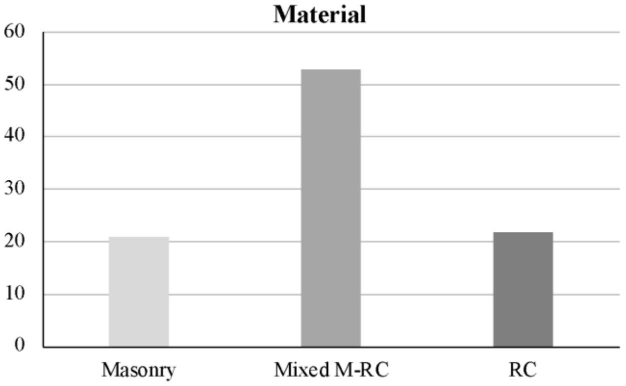

Figure 1. Distribution of school buildings of the stock based on construction materials.

RC has been used in the past mostly for multi-storey school buildings, thus the analysed portion of the stock is mainly composed by primary and secondary school, often located in multi-storey buildings, rather than pre-schools which are often one-storey buildings (Figure 2).

In order to achieve a basic level of knowledge of the structures, a preliminary research of documentation has been carried out. The gathered information concerns: building geometry and resisting system, materials used, and in some cases construction details. The first step for the assessment of each building is the execution of an on-site survey in order to collect information about the structure and to verify the consistency of the documentation with the as-built configuration. A complete photographic, geometrical and structural survey has been carried out for each school building, resulting in a more time-consuming operation for those school buildings with poor archive documentation.

4.1 *Typological and structural characterisation*

Typological and structural characterisation has been carried out in order to understand the stock composition and identify homogeneous vulnerability classes.

Figure 3 shows the distribution of years of construction and it is possible to observe that school buildings were mostly built from 60s to 80s. Thus, most part of the stock has been designed only for gravity loads, without seismic conceptions and details. The stock does not include any RC structures built from 1996 to 2003 and designed with DM 09/01/96. Statistics of number of storeys are presented in Figure 4. Primary and secondary school buildings are always multi-storey, while nurseries and pre-school structures are generally one-storey, with only one nursery located in a two-storey building. Figure 5 presents an overview of the distribution of plan area, which tends to increase with the level of education, as expected.

Figure 6 shows the distribution of lateral resisting systems observed. The most frequent structural system is the bidirectional frame, already used in the late 70s as shown in Figure 7, where the evolution of lateral resisting systems over the decades is presented. After OPCM n. 3274 entered into force in 2003 3D lateral resisting systems (i.e. 3D frames and mixed wall-frame systems) have been the preferred solutions.

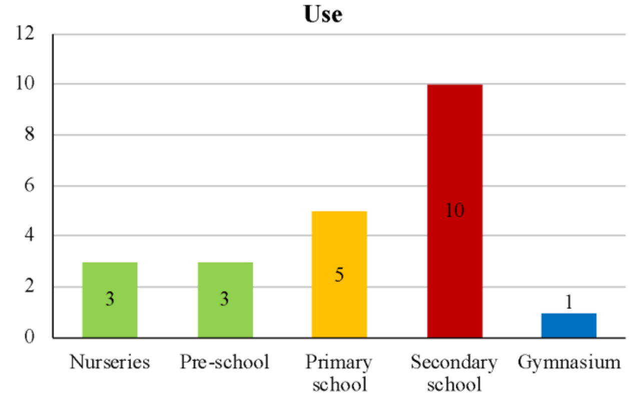

Figure 2. Distribution of school buildings of the stock based on their use.

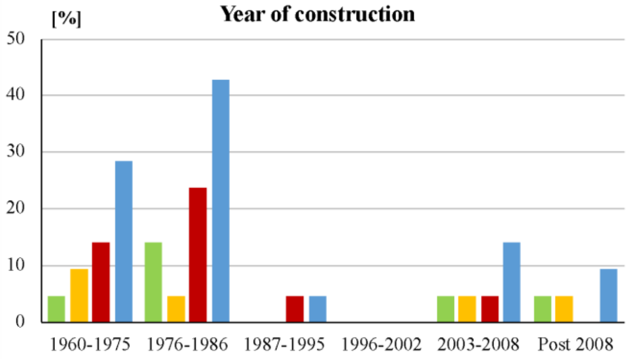

Figure 3. Distribution of school buildings of the stock based on year of construction.

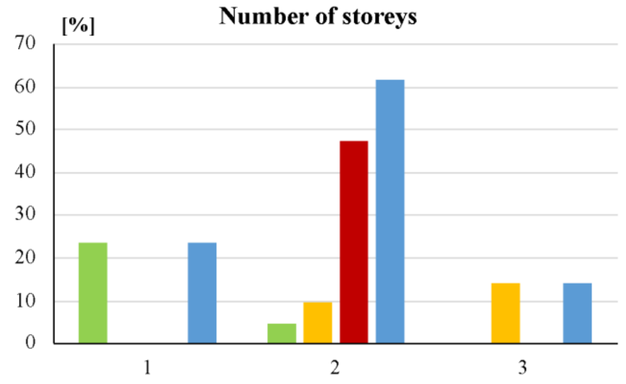

Figure 4. Distribution of school buildings of the stock based on number of storeys.

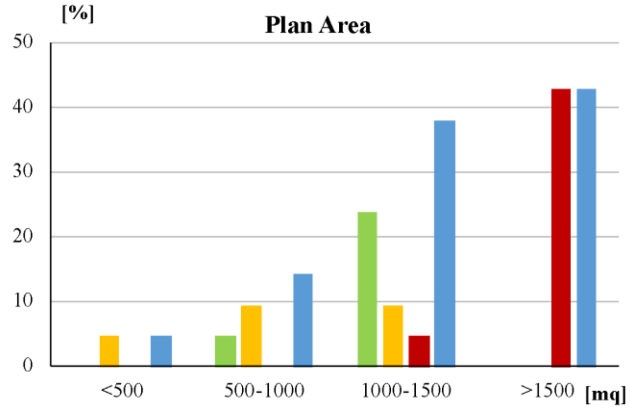

Figure 5. Distribution of school buildings of the stock based on plan area.

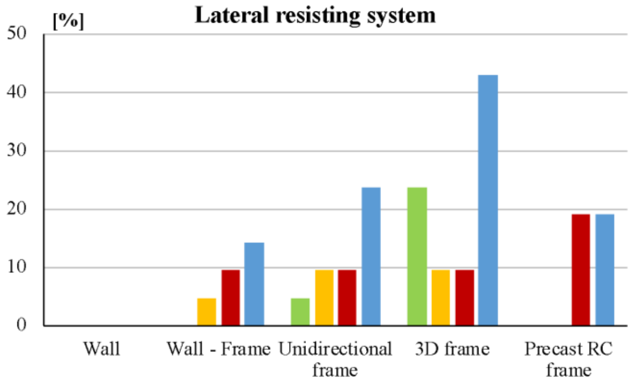

Figure 6. Distribution of school buildings of the stock based on lateral resisting system.

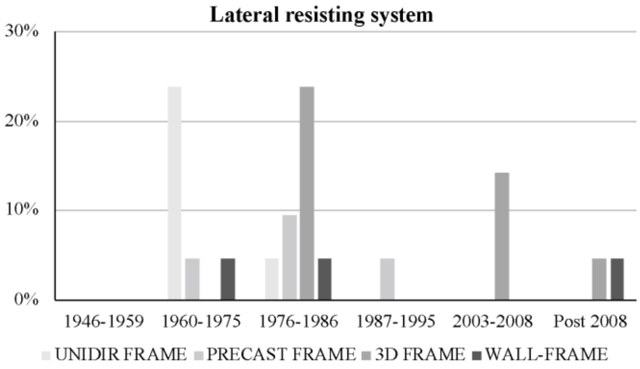

Figure 7. Distribution of lateral resisting system by year of construction for RC buildings of the stock.

🟩 NURSERIES AND PRE-SCHOOL 🟨 PRIMARY SCHOOL 🟥 SECONDARY SCHOOL 🟦 TOTAL 🟦 GYMNASIUM

Table 2. Vulnerability classes identified from the RC analysed stock.

Lateral resisting system	*Year of construction*	*No. of storeys*	*Plan Area [mq]*	*Floor*	*Column dim. [cm]*	*Concrete class*	*Long bars [%]*	*Stirrups*
C1: Prefabricated frame	1975-1987	2	>1500	C.A.	35-45	C35/45	1	Φ5/20
C2: Unidirectional frame	1960-1975	2-3	800-1500	C.A.	25-45	C25/30	0.70	Φ6/20
C3: Bidirectional frame	1976-1986	1	1000-1500	C.A.	25-40	C25/30	0.70	Φ6/20
C4: Bidirectional frame	1976-1986	2-3	>1000	C.A.	30-40	C25/30	0.80	Φ6/20
C5: Bidirectional frame	Post OPCM 2003	2-3	1200-2000	C.A.	40	C30/37	1.30	Φ8/15
C6: Bidirectional frame	Post OPCM 2003	1	1000-1500	Timber	30-40	C25/30	0.90	Φ8/7

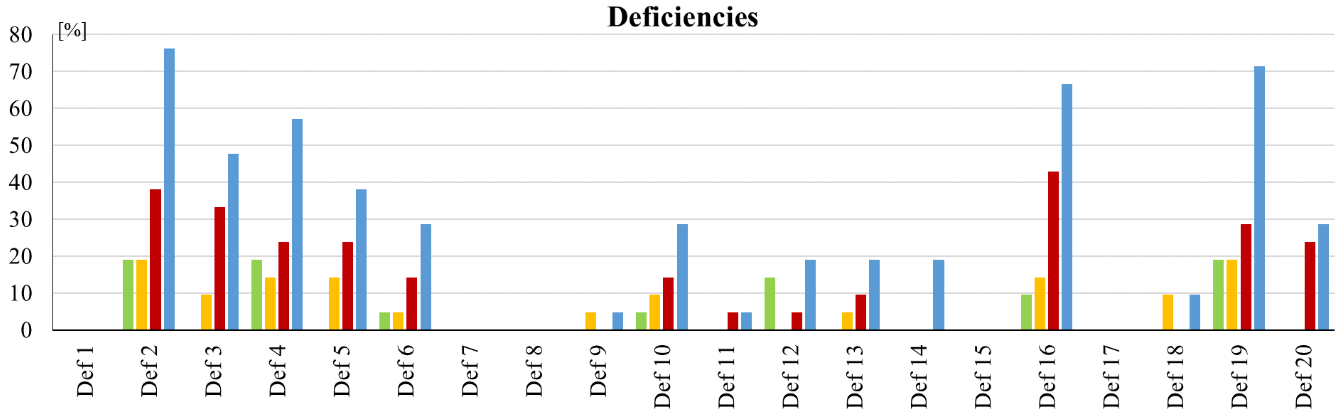

Figure 8. Distribution of surveyed deficiencies for the analysed RC building stock.

Table 3. Deficiencies verified by improved Ordinanza n. 14/2013 form.

No.	Deficiencies	
Def. 1	Plan irregularity ($L_{min}/L_{max}>5$)	β
Def. 2	Plan irregularity (not symmetrical or compact)	β
Def. 3	Flexible floors	β
Def. 4	Eccentricity centre of masses/stiffness	β
Def. 5	Cores eccentricity	β
Def. 6	Weak direction	α
Def. 7	Mass irregularity (elevation)	β
Def. 8	Soft storey (severe)	α
Def. 9	Soft storey (moderate)	β
Def. 10	Short column effect due to infills	α
Def. 11	Partition out of the structural grid	β
Def. 12	Weak column/strong and heavy beam	β
Def. 13	Column brittle fracture (severe)	α
Def. 14	Column brittle fracture (moderate)	β
Def. 15	Widespread degradation of structural elements	β
Def. 16	Pounding (non-seismic joints)	β
Def. 17	High axial load on columns (severe)	α
Def. 18	High axial load on columns (moderate)	β
Def. 19	Vulnerability of non-structural elements	β
Def. 20	Precast structures vulnerability	α

The analysis of the distribution of typological and structural characteristic in the stock allows defining homogenous vulnerability classes, as indicated in Table 2.

4.2 Results of the seismic vulnerability assessment

4.2.1 Analytical assessment

Vulnerability assessment through analytical method was performed with improved Ordinanza n. 14/2013 form for deficiencies count. Table 3 shows the list of deficiencies verified and the severity level (alpha for severe deficiency or beta for moderate deficiency). The distribution of surveyed deficiencies is presented in Figure 8.

The most frequent surveyed severe deficiencies are weak direction, short column effects due to infills and precast structures vulnerability such as loss of support and brittle fracture of the saddles.

It has to be pointed out that the weak direction deficiency, which affects a large number of surveyed school buildings at least in one structural unit, was not considered in the original Ordinanza n.14/2013 form for RC buildings. The most frequent surveyed moderate deficiencies are plan irregularity, in terms of plan shape and eccentricity between the centre of masses and centre of stiffness, vulnerability of non-structural elements (e.g. chimneys) and risk of pounding due to the lack of seismic design joints between structural units (expansions joints or adjacency without joints have been largely observed).

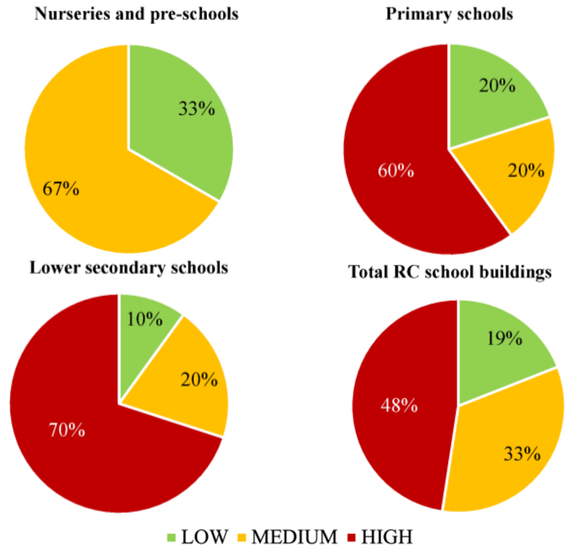

Figure 9. Degree of deficiencies for RC building stock.

The degree of deficiencies (high, medium or low) for each school building is defined by the number of alpha and beta observed, as mentioned above. Results in terms of degree of deficiencies for different levels of education are presented in Figure 9. Nurseries and pre-schools, basically one-storey buildings, present less vulnerability factors than primary and secondary schools which are often multi-storey buildings.

The introduction of seismic design provisions, in Italy with OPCM n. 3274/2003, allowed improving the building conception in terms of seismic performance, not only increasing lateral loads that structural elements must resist to, but also inducing to avoid those configurations that increase seismic vulnerability (e.g. plan irregularity, storey offset or floating columns). School buildings of the stock designed with seismic provisions after 2003 present a significant reduction in mean degree of deficiencies as shown in Figure 10.

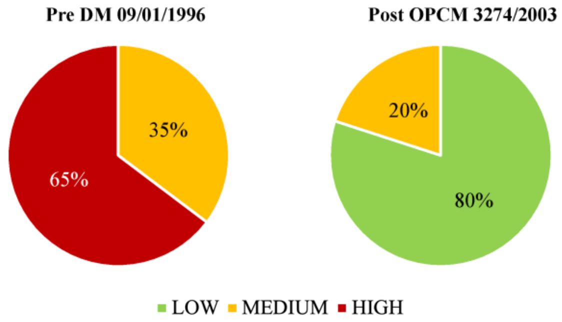

Figure 10. Degree of deficiencies based on design provisions: gravity load design (Pre DM 09/01/96) or seismic design (Post OPCM 3274/2003)

4.2.2 *Mechanical assessment*

Mechanical assessment has been carried out on the 22 RC buildings of the stock through the simplified method FIRSTEP-RC; moreover, the simplified assessment with single-dof cantilever scheme has been applied to 5 gymnasium structural units, which present flexible roofs. The mechanical procedure allows calculating the resistance acceleration (Equation 1). No interaction between structural units is taken into account. The capacity/demand ratio for building classification is calculated taking the minimum resistance capacity for each direction and structural unit.

In those cases where data about reinforcement steel were unavailable, minimum reinforcements have been used to assess the capacity of structural elements according to coeval codes, resulting in a conservative assessment.

Local verification of joints results to be very demanding for existing structures not designed for seismic loads; furthermore, shear resistance is calculated considering concrete elements without stirrups (§4.1.3.2.5.1 of NTC2018), whose formulation provides conservative results compared to the new formulation from Circolare 2019 for shear resistance under cyclic actions (C8.7.2.3.5). Unfortunately, this formulation requires more information about reinforcement and details, making it difficult to use it in a framework of expeditious assessment of an entire stock. Furthermore, the formulation of shear resistance for concrete elements without stirrups tends to penalise recent structures whose shear resistance considering transverse reinforcements is generally higher.

Figure 11 shows results in terms of seismic capacity/demand classification. Most structures appear to be classified F. Simplified mechanical methods are generally conservative because they implement models and verification formulas defined for design of new structures. Nevertheless, results are consistent in terms of priority-ranking which is the main objective of the proposed procedure.

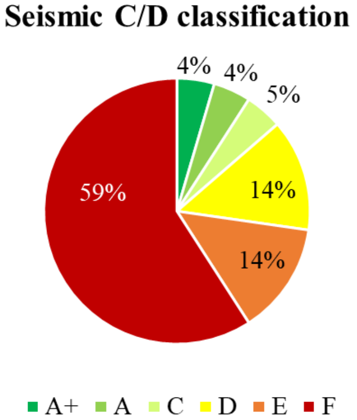

Figure 11. Distribution of seismic classes for RC buildings of the stock.

4.2.3 *Priority-ranking list*

As previously mentioned, simplified mechanical models may neglect some fundamental aspects for seismic vulnerability assessment. In particular, FIRSTEP-RC analysed the structure at the ground floor; thus, it cannot increase vulnerability due to elevation irregularity, soft-storey mechanism, short column effect due to infills or pounding between structural units. Believing that some of these aspects may heavily affect seismic performance, a greater weight has been given to analytical assessment results. Buildings are ranked according to their degree of deficiencies, decreasing from high to low. For the same degree of deficiencies, school buildings are ranked by increasing capacity/demand ratio.

5 CONCLUSIONS

The paper describes a new procedure to assess the seismic vulnerability of school buildings combining a qualitative analytical method resulting in a degree of deficiencies and a quantitative capacity/demand ratio from simplified mechanical model from literature.

The mechanical model used appears to be conservative and provides low resistance acceleration due to various aspects. First of all, a linear analysis is implemented, and thus global capacity is defined as the first element reaches its ultimate limit state, providing conservative results in terms of overall structural response. Secondarily, some resistance formulations, such as shear resistance, have proven to be conservative in the assessment of existing structures. At the moment, a specific formulation for existing buildings is available, but it requires a lot of information thus it is not suitable for expeditious stock evaluation with the proposed methodology. At last, mechanical models for RC structures require the knowledge of steel reinforcement, fundamental for resistance calculation. In some cases, this kind of information was not available, thus minimum reinforcements according to coeval codes have been used, resulting in even more conservative outcomes.

Nevertheless, results are consistent in terms of priority-ranking, which is the main objective of the proposed procedure.

Results from the analytical method and the mechanical model have been combined to achieve a priority list for interventions. A greater weight has been given to analytical assessment results in order to take into account some aspects neglected by the mechanical model but strongly affecting seismic performance. Buildings are ranked according to their degree of deficiencies, decreasing from high to low. For the same degree of deficiencies, school buildings are ranked by increasing capacity/demand ratio.

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