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# Seismic assessment and loss estimation of existing school buildings in Italy

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ABSTRACT

Extensive damage to school buildings has been observed during past earthquakes in Italy and there is a need to better understand their potential vulnerability. As part of a national project to assess seismic risk in Italian schools, a database was compiled in terms of characteristics such as school location and construction typology. This paper examines a number of these buildings considered to be a representative sample of the Italian school building population. To quantify their seismic vulnerability, the induced damage with respect to increased shaking intensity need to be quantified. This characterisation of the building vulnerability, in combination with the seismic hazard, allows more informed, risk-based decisions to be made using performance metrics such as expected annual loss (EAL). This article outlines a case study application quantifying the EAL and collapse safety for three school buildings representative of the Italian school building stock. Detailed numerical models were developed using information collected during in-situ inspections in order to accurately represent the dynamic response of the school structures. To estimate economic losses, a structural and non-structural element inventory was compiled using in-situ survey information. This case study application is conducted in a systematic fashion to clearly illustrate the various details required to implement more advanced seismic assessment studies. Finally, a comparison is made with the seismic classification guidelines recently introduced in Italy to provide further insight into how these can be used to identify existing buildings vulnerable to excessive damage and potential collapse during earthquakes.

## 1. Introduction

The seismic vulnerability of existing school buildings in Italy has received much attention following the 2002 Molise earthquake in Southern Italy, which resulted in the collapse of the Iovene primary school in San Giuliano killing 27 students and one teacher. To address this issue, the European Centre for Training and Research in Earthquake Engineering (EUCENTRE) initiated a research project entitled ‘*Progetto Scuole*’, with the main objective of seismically assessing a number of school buildings throughout Italy that can be considered representative of the existing school building stock. Survey information [1] showed that the majority of reinforced concrete (RC) frame school buildings were constructed prior to the 1970s with little to no consideration of modern seismic design principles. These RC buildings were typically designed for gravity loads only and involved using allowable stress and other such design provisions specified in Regio Decreto 2229/1939 [2] along with other common construction conventions prior to the introduction of seismic design provisions [3]. A common feature of these gravity load-only designs identified in O’Reilly et al. [4] is the complete lack of capacity design considerations in the beam and column members of RC frames. The columns were sized principally for axial loading and the beam members were designed by considering the hogging and sagging moments of a continuously loaded multi-support beam. This approach was quite common during the construction boom that followed World War II across southern Europe and gave rise to many RC structures vulnerable to undesirable seismic response, as highlighted during past earthquakes [5–8]. Unreinforced masonry buildings (URM) were also seen to represent a significant portion of the building stock in Italy, with many being historical and/or old masonry buildings known to be seismically vulnerable [9]. For example, field observations from the Emilia Romagna earthquake in 2012 [10] underlined this through numerous partial collapses observed in historical masonry buildings. Furthermore, the presence of large thin unsupported clear lengths of masonry can result in the wall ejection mechanism, a type of behaviour observed in scholastic structures in L’Aquila [11], for example. The response of URM buildings not vulnerable to this kind of local failure mode is generally governed by in-plane behaviour of the walls, causing piers and spandrel damage. Spandrel shear and flexural failure has been

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commonly observed in the past [10] and is mainly related to the quality of the supporting lintels [12]. In addition, another common damage mechanism is pier member damage [10], accompanied by shear diagonal cracking similar to that observed in spandrels. In some cases, the lack of maintenance contributed to increase the seismic vulnerability of existing masonry buildings, such as the degradation of timber, which can reduce the efficiency of the floor system to provide rigid diaphragm action when transferring inertial forces to the lateral load resisting system. Precast Concrete (PC) structures have also been used extensively in Italy, most commonly for industrial buildings. The seismic vulnerability of this structural typology has been observed in numerous past earthquakes, in particular the 2012 Emilia earthquakes, which resulted in a significant number of casualties and economic losses. From post-earthquake reconnaissance, Magliulo et al. [13] reported that the observed damage in PC buildings was mainly related to either loss of support of horizontal elements or the collapse of cladding panels, with both cases being the result of poor connection detailing. The poor seismic detailing that is typical in these buildings is likely to be a result of the first specific precast regulations only being published in 1987 in Italy.

A significant portion of the total losses in recent earthquakes worldwide has been attributed to damage to non-structural elements, which occurs at low levels of ground shaking and can significantly affect the post-earthquake functionality of buildings. Typical damage is related to ceiling systems, piping systems, infill walls and building contents. An example of extensive damage to non-structural elements was reported by Miranda et al. [14] following the 2010 Maule Earthquake in Chile; the Santiago International Airport was closed for several days due to significant damage to piping and ceiling systems, while four hospitals completely lost their functionality and over ten lost 75% of their functionality due to damage to fire sprinklers. Braga et al. [15] reported extensive in-plane and out-of-plane damage to masonry infills in RC buildings during the 2009 L'Aquila Earthquake in Italy. Likewise following the 2012 Emilia Earthquake, where storage rack systems in industrial facilities were the most affected components [16]. Calvi et al. [17] conducted an exhaustive review of typical non-structural damage observed in school buildings after major seismic events around the world and highlighted that ceiling systems, partitions, lighting systems and bookshelves are generally the most vulnerable elements. The main reasons identified were the lack of proper anchorage of the various elements and, in many cases, the absence of clear seismic design methodologies and prescriptions to implement.

In terms of assessing the performance of buildings and their structural and non-structural elements, one of the most comprehensive PBEE methodologies was initially conceived by Cornell and Krawinkler [18] and then adopted by the Pacific Earthquake Engineering Research Center (PEER). This PEER-PBEE framework includes a number of stages, illustrated in Fig. 1.1, with hazard, structural, damage and loss analysis being conducted to provide information for a final consequence analysis of performance measures referred to as decision variables (DV), such as the expected losses and also collapse safety. The practical implementation of each individual step of this framework has also been described in detail by Gunay and Mosalam [19].

If one considers the expected monetary losses due to the repairs required at each intensity measure (IM) level, the expected annual loss (EAL) of a building for a given site location can be computed by integrating the expected direct economic losses expressed as a function of IM over the site hazard curve obtained from PSHA, as indicated in Eq. (2):

$$\mathrm{EAL} = \int \mathrm{E}[\mathrm{L_T}\ |\mathrm{IM}] \left| \frac{\mathrm{d}\lambda}{\mathrm{dIM}} \right| \mathrm{dIM} \tag{2}$$

where $\mathrm{E}[\mathrm{L_T}|\mathrm{IM}]$ represents the total expected direct economic losses for a given definition of IM and site D, as described above.

In 2017, the Italian Ministry of Infrastructure and Transport issued Decreto Ministeriale 58/2017 [20] outlining a framework with which to classify the seismic risk of buildings. The building's seismic performance is described in terms of EAL and structural collapse capacity, which are employed to give an overall rating on a letter-based scale from A+ to G, similar to the appliances energy consumption scale used in Europe [21]. This framework is integrated with the existing Italian code [22] to provide practitioners with a more simplified method and metric to assess the overall seismic performance of buildings via retrofitting.

This paper examines the seismic loss assessment of buildings by characterising and comparing the vulnerability of existing school buildings in Italy using the PEER-PBEE detailed framework outlined in the FEMA P58 document [23]. This is implemented in a systematic fashion, whereby a representative sample of three buildings from the entire existing school building stock was identified and examined in detail, involving the collection of data regarding both the structural configuration and the non-structural element inventory. Detailed numerical models were constructed for each school building to characterise the seismic response to increasing seismic intensity, which was then used in conjunction with the inventoried list of damageable components identified during in-situ inspections of each school building to conduct a detailed loss estimation study for each of them. This was performed for three different building construction typologies, namely RC frames with masonry infill, URM buildings and PC frames, typically found throughout Italy. The results of this study allow for the vulnerability of each school building typology to be characterised and compared. Furthermore, it is hoped that the detailed case study application presented herein will encourage more practitioners to use available comprehensive methods to assess seismic vulnerability of existing buildings. Lastly, comparison of the detailed analysis conducted here with the recent Italian guidelines to classify seismic risk is discussed in order to illustrate some differences and potential future improvements to the guidelines.

## 2. Case study school buildings

A number of school buildings comprising different structural typologies were selected for this study. Available information on over 49,000 Italian schools [1] was examined to determine the prevalent

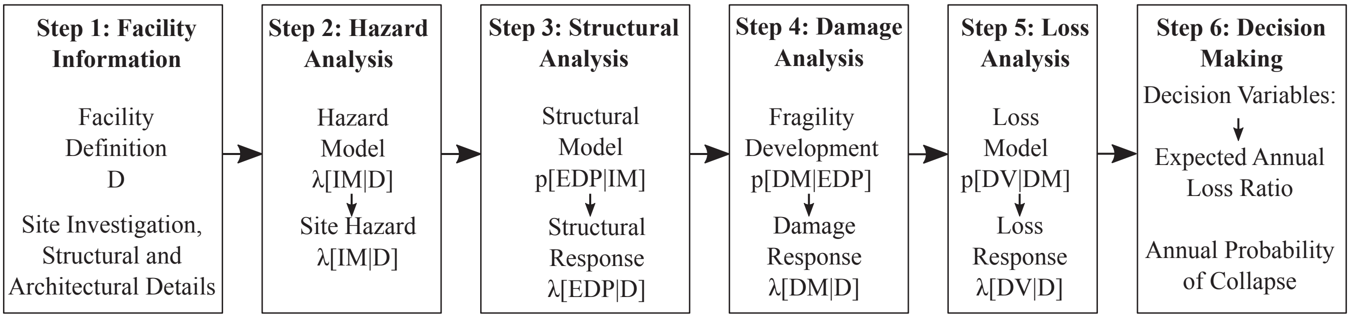

**Fig. 1.1.** Illustration of the four stages of the PEER-PBEE framework [18].