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Fragility curves for residential unreinforced masonry buildings prone to out-of-plane mechanisms: the case of the historical center of Sora

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Abstract

The earthquake events of the past and recent years highlight as the seismic protection of historical towns is a crucial and current issue in Italy, but also in many other earthquake prone areas of Europe, where severe damages and collapse of buildings have been observed after seismic events. In particular, significant damages have been detected in historic centers of small and medium towns, mainly characterized by unreinforced masonry buildings, highly vulnerable with regard to out-of-plane collapse mechanisms. In this context, the assessment of the seismic vulnerability of unreinforced masonry buildings is a fundamental issue, in that they represent the most widespread construction typology in Italian and European small and medium towns. One of the most effective approaches in predicting potential damages of building typologies, is based on the derivation of fragility curves. An important aspect that affects the construction of fragility curves is the choice of response spectra to define the seismic demand; both Italian code and European guidelines allow the use of natural records, but also propose to employ smoothed spectra, in that the first one is hardly applicable by practitioners. Nevertheless, the employment of the smoothed spectra does not allow for adequate considerations about the influence of record-to-record variability. Downstream of this brief discussion, the paper presents the evaluation of fragility curves for unreinforced masonry buildings typical of the Central Italy, prone to the occurrence of out-of-plane collapse mechanisms, by considering both the spectral-shapes directly derived from the Italian codes and spectra obtained by the selection of natural accelerograms.

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1. Introduction

In the past and recent years, the integrity of building heritage of the small and medium Italian historical towns has been mostly affected by earthquakes. In particular, the observed damages and collapses particularly highlight the fragilities of unreinforced masonry buildings, often highly vulnerable with regard to out-of-plane collapse mechanisms, as underlined by the available literature studies (Sorrentino et al. (2017), Moon et al. (2014) and Lourenço et al. (2011)).

In the last years particular attention has been devoted to the development of approaches for the assessment of the seismic vulnerability of historical towns, some of which carried out with reference to historical towns of Central Italy - Sandoli et al. (2021, 2022), Zucconi et al. (2021), Cima et al. (2021b, a).

In this context, the aim of the paper is to propose an approach for evaluating fragility curves of unreinforced masonry buildings typical of Central Italy with regard to out-of-plane mechanisms. A fundamental aspect that affects the construction of fragility curves is the choice of adequate response spectra to define the seismic demand. In this framework, both Italian code and European guidelines, besides allowing the use of natural records, propose the employment of smoothed spectra, which are of simpler use for practitioners. Nevertheless, the employment of the smoothed spectra could not allow for adequate considerations about the record-to-record variability.

Following the above discussion, this paper presents an approach for the evaluation of fragility curves by considering both the smoothed spectra proposed by the Italian codes and those obtained by selecting combinations of natural accelerograms, in order to analyze their effects on the fragility curves. For the selection of the natural accelerograms and the consequent evaluation of spectra, the software REXEL, developed by Iervolino et al. (2009), is here adopted.

The proposed approach refers to unreinforced masonry building typologies typical of Central Italy, prone to the occurrence of out-of-plane collapse mechanisms which are the most commonly observed in historical buildings after seismic events, as reported by D'Ayala and Speranza (2003). In particular, specific reference has been made to the building typologies characterizing the historical center of a medium size town of Central Italy, here assumed as case study.

2. Fragility curves for building typologies prone to overturning collapse mechanisms

The paper presents an analytical approach for deriving the fragility curves for macro-typologies of masonry buildings representative of a specific regional area in Italy and prone to the occurrence of out-of-plane collapse mechanisms in case of seismic actions.

The approach has been applied with specific reference to two building typologies characterizing the historical center of Sora (Fig. 1), a medium size town of central Italy in the province of Frosinone (Lazio Region). The building typologies have been identified using the data collected within the research project CARTIS (DPC/ReLUIS 2019–2021) and their main characteristics are reported in Table 1 and named "MUR 1" and "MUR 2". As shown in Table 1, the two building typologies show similar characteristics in terms of number of storeys, average storey heights, intended use and roof configuration but they differ for the age of construction and the type of masonry: the buildings of "MUR 1" have been built before 1860 and they are made of irregular masonry with rough stones, while those belonging to "MUR 2" have been built between 1861 and 1945 and they are made of regular masonry with square stones.

For each building typology, the approach starts with a preliminary analysis finalized to identify the out-of-plane collapse mechanisms that are the most likely to activate. This phase is performed according to the qualitative approach proposed by Saccucci et al. (2021) on the basis of the geometrical, typological and constructive features of each building, including the presence of structural details which impair or avoid the activation of out-of-plane mechanisms. The knowledge of the building's features is obtained from survey activities and consultations of archival documents and databases carried out by the authors within the research project CARTIS, as reported in Zuccaro et al. (2015).

Fig. 1. View from above of the historical center of Sora.

On the basis of the preliminary investigation, the buildings have been divided into categories, each one characterized by the same failure mechanism and the same number of floors. With reference to the categories of the buildings prone to the overturning mechanisms, virtual populations of 3000 buildings have been generated for each category by varying their geometrical and mechanical parameters within ranges consistent to the collected data. To this purpose, the Monte Carlo procedure has been applied by varying the following parameters: wall thickness, inter-story height, percentage of the holes in the façade and compressive strength of the masonry. In particular, the values of the geometrical characteristics have been generated by considering a lognormal distribution with the mean and the standard deviation derived from the collected data. The values of the compressive strength of the masonry have been generated by considering a lognormal distribution with the mean and the standard deviation suggested by CNR-DT212 (2014).

Table 1. Characteristics of the building typologies identified in the historical centers of Sora.

Building typology	MUR 1	MUR 2
Type of masonry	Irregular masonry with rough stones	Regular masonry with square stones
Age of Construction	<1860	1861-1945
Number of stories	2-3	2-3
Average height of stories	2.5-3.49 m	2.5-3.49 m
Intended Use	Residential use, storage use	Residential use, commercial use, storage use
Slabs	Made of wood, oriented mainly parallel to the facade	In hollow core concrete, oriented mainly parallel to the facade
Roof	Gabled roof, oriented mainly parallel to the facade	Gabled roof and flat roof, oriented mainly parallel to the facade
Materials of the roof	Timber and reinforced concrete	Timber and reinforced concrete

Then, for each building of the virtual populations, the capacity curves, expressed in terms of spectral acceleration, a, versus the spectral displacement, d, have been evaluated by applying the nonlinear kinematic analysis suggested by Circolare (2019). In the analysis, a bilinear model under the hypotheses of rigid block, no-tensile strength, absence of sliding between blocks and limited compressive strength has been even adopted. For the sake of brevity, in Fig. 2a are reported the capacity curves obtained only for the category of 3-story buildings, prone to the partial overturning of the second and the third story and belonging to "MUR 1".

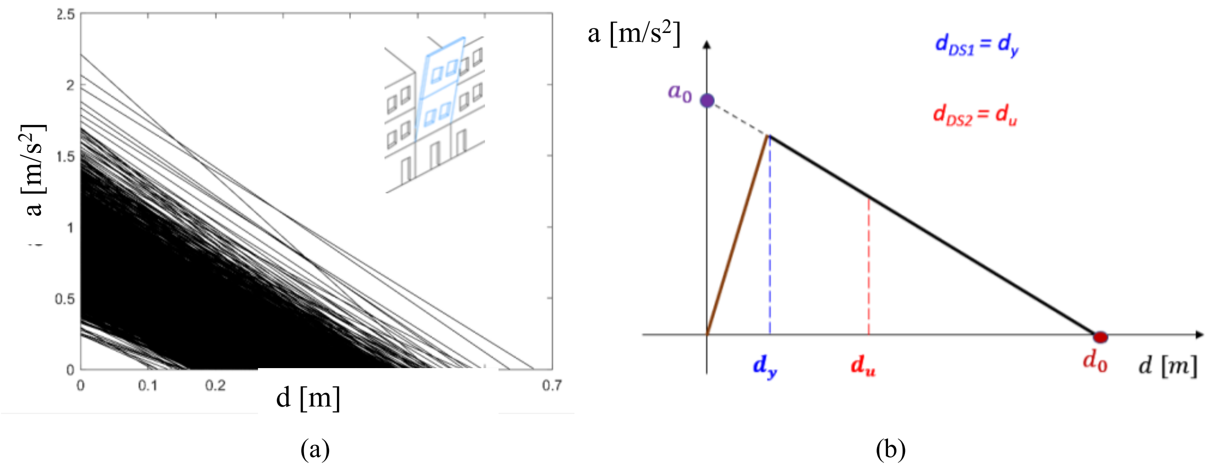

Fig. 2. (a) Capacity curves of 3-story buildings category belonging to MUR 1 with partial overturning of the 2nd and the 3rd story; (b) damage thresholds.

Subsequently, in order to derive the fragility curves for the moderate (DS_1) and the complete Damage State (DS_2) in correspondence of the Damage Limit States (DLS) and the Safeguard life Limit State (SLS), suggested by the Italian Code, respectively, the following damage thresholds d_{DSi} have been evaluated starting from the obtained capacity curves (see Fig. 2b):

$$d_{DS1}=d_y \tag{1}$$

$$d_{DS2}=d_u \tag{2}$$

where:

- d_y is the spectral displacement corresponding to the activation of the mechanism at the DLS, given by the intersection between the capacity curve of the mechanism and a pseudo-elastic branch that describes the response of the structure until the activation of the mechanism, as reported by Lagomarsino (2015);
- d_u is the spectral displacement representative of the achievement of the SLS, equal to the 40% of the spectral displacement corresponding to a spectral acceleration equal to zero, d_0, as reported by the Circolare (2019).

Then, the maximum displacement demand for each damage level, D_{DSi}, in terms of the maximum spectral displacement requested to the mechanism, has been defined by applying the Capacity Spectrum Method (Freeman, 1998). To this purpose, the spectra derived from spectrum-compatible natural records selected through the software REXEL developed by Iervolino et al. (2009) have been considered. For the selection, reference made to target-spectra defined according to the Italian Code (NTC18) in correspondence of 8 different return periods T_R, between 30 and 975 years. It should be pointed out that for the application of the CSM a distinction has been made on whether the collapse mechanism occurs at the base of the ground floor of the building (z=0) or at the base of the upper floors (z>0). In the first case the ground displacement spectra have been used, while in the second one floor displacement spectra have been considered.

Once determined the seismic demand, the Damage Indices DI_{DSi} for the two damage limit states DS_i have been evaluated as the ratio between the maximum displacement demand, D_{DSi}, and the damage threshold, C_{Dsi}. Finally, for each category, the fragility curves corresponding to the two DS_i have been derived, considering the Peak Ground Acceleration, PGA, as an indicative parameter of the intensity of the seismic input.

In particular, assuming a log-normal distribution of the DI_{Dsi} conditioned on a given value of PGA, the following equation has been used for deriving the fragility curves, as reported in the guidelines of the CNR-DT212 (2014):

$$f_{DSi} = p\left(DI_{DSi} \geq 1_{|PGA}\right) = 1 - \Phi\left(\frac{\ln 1 - \mu_{\ln DI_{DSi|PGA}}}{\sigma_{\ln DI_{DSi|PGA}}}\right) = \Phi\left(\frac{\mu_{\ln DI_{DSi|PGA}}}{\sigma_{\ln DI_{DSi|PGA}}}\right) \tag{3}$$

where:

- $\Phi[\bullet]$ is the lognormal standard distribution function;
- $\mu_{\ln DIi|PGA}$ is the mean value of the logarithm of the variable DI_{DSi} conditioned on the given value of PGA;
- $\sigma_{\ln DIi|PGA}$ is the dispersion of the natural logarithm of the variable DI_{DSi} conditioned on the given value of PGA.

The conditional mean values of the variable DI_{DSi} have been defined for each value of the PGA through the following expression proposed by Nielson and DesRoches (2007):

$$\mu_{\ln DI_{DSi|PGA}} = A_{DSi} + B_{DSi} \cdot \ln\,(PGA) \tag{4}$$

where A_{DSi} and B_{DSi} are coefficients obtained by a linear regression of the logarithm of the DI_{DSi} versus the logarithm of the PGA (see Fig. 3).

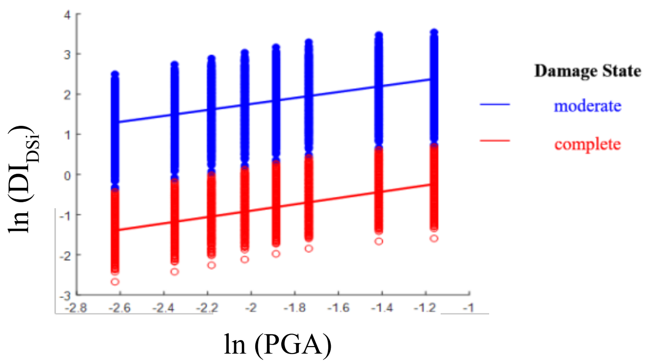

Fig. 3. Linear regression of the logarithm of the DI_{DSi} versus the logarithm of the PGA.

The dispersion values have been evaluated through the following equation:

$$\sigma_{\ln ID_{DSi|PGA}} = \sqrt{{\sigma_{m\,i}}^2 + {\sigma_{rtr\,\sigma rtr\,i\,i}}^2} \tag{5}$$

where:

- $\sigma_{m\,i}$ represents the uncertainty of the model, estimated applying the following equation:

$$\sigma_{m\,i} = \sqrt{\frac{\left(\sum_{j}^{nPGA} \ln(DI) - (A_{DSi} + B_{DSi} \cdot \ln(PGA))\right)^2}{n-2}} \tag{6}$$

being DI the value of the Damage Index evaluated by considering the mean selected records;

- $\sigma_{rtr\,i}$ represents the uncertainty due to the record-to-record variability, estimated as reported by Lagomarsino and Cattari (2014) by the following expression:

$$\sigma_{rtr\,i} = \frac{1}{2} \cdot \left|\overline{\ln DI_{16}} - \overline{\ln DI_{84}}\right| \tag{7}$$

where DI_{16} and DI_{84} are the value of the Damage Indices calculated considering the 84^{th} and 16^{th} percentile of the selected records, respectively.

3. Discussion and results

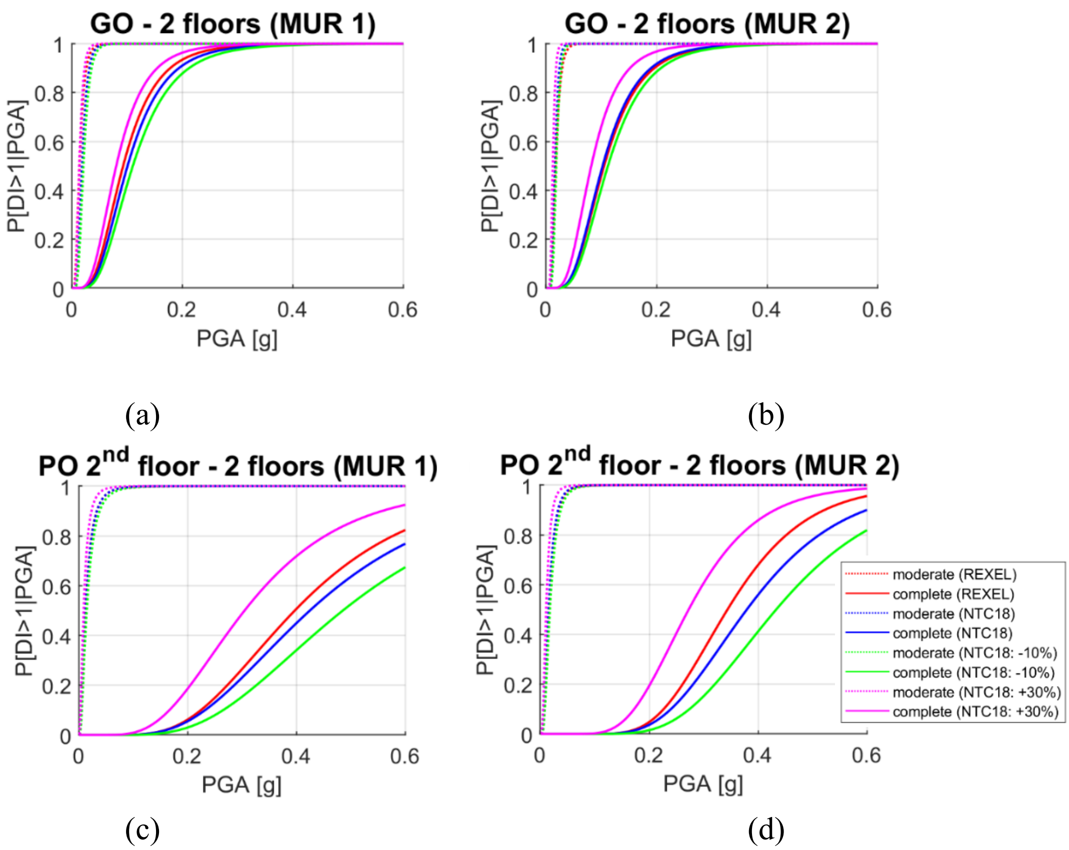

Fig.4. Fragility curves for the populations of two-story buildings, be part of the two structural typologies MUR 1 and MUR 2 prone to: (a) global overturning mechanism - MUR1; (b) global overturning mechanism - MUR2; (c) partial overturning mechanism – MUR 1; (d) partial overturning mechanism – MUR 2.

The results obtained by the procedure described in the previous section are herein reported in terms of fragility curves. In particular, the fragility curves reported in Fig. 4 refers to the category of two-story buildings, belonging to "MUR 1" and "MUR 2", prone to the global overturning mechanism (Fig. 4a and b) and to the partial overturning mechanism (Fig. 4c and d). In the figures, the red curves are obtained by considering the spectral shapes derived by natural accelerograms (REXEL), while blue curves are evaluated by considering the smoothed spectra proposed by the Italian code (NTC 18). In the same figures, green curves are evaluated by considering the smoothed spectra of the Italian code reduced by 10%, while magenta curves are those obtained by the smoothed spectra amplified by 30%, i.e. the range of tolerance imposed to derive natural spectra compatible with the target spectrum provided by the Italian code.

In this context, it is important to highlight that, in both the cases of the spectral shapes derived by REXEL and the smoothed spectra proposed by the Italian Code, the record-to-record variability has been taken into account by means of the dispersion $\sigma_{rtr\,i}$ referred to the natural records (eqn. 7). It means that blue and red curves have the same value of dispersion related to record-to-record variability, but different model dispersions and different values of the conditional mean values $\mu_{\ln D_i|PGA}$. These latter (see eqn. 4) indeed depend on the capacity curves, which are the same in the two cases, and on the seismic demand, which, on the contrary, is different.

From plots it is possible to observe that both the curves related to the moderate damage and the ones related to the complete damage are included between green and magenta fragility curves (i.e. the admissible range provided by Italian code). This result suggests that, for the sake of simplicity, it could be possible to obtain realistic results by employing the smoothed spectra derived by the Italian Code (NTC18), provided that a record-to-record variability is derived a priori on natural records. Figure 4, also, shows that, for complete damage, the red curve is perfectly overlapped to the blue one for the global overturning of "MUR 2", while in all other cases the red one overhangs the blue one; it means that, in the latter cases, the fragility curves derived with natural spectra provides a larger vulnerability, also if similar to that provided by the smoothed spectra, which therefore provide realist results.

4. Conclusions

In the context of preservation of the existing building heritage, the evaluation of the seismic vulnerability assumes a fundamental role as it allows to identify buildings that need seismic improvement interventions. In this framework, particular attention should be devoted to unreinforced masonry buildings, which are the most common in Italian historical centers and are highly vulnerable to out-of-plane mechanisms.

The paper presents an approach to derive fragility curves of unreinforced masonry buildings towards the out-of-plane mechanisms for a large-scale vulnerability assessment. The approach has been applied to virtual population of buildings, generated starting from the geometrical and mechanical characteristics collected during a survey campaign of a sample of buildings belonging to a typical historical center of central Italy; then, the fragility curves have been evaluated for both global and partial overturning mechanisms.

The focus of the paper is the analysis of the influence of the record-to-record variability in the derivation of fragility curves. Indeed, the curves here presented with reference to a case study have been obtained by considering both natural spectral shapes and smoothed spectra proposed by the Italian code, assuming the same value of dispersion due to the record-to-record variability. The comparison among the obtained curves has underlined similarities among the curves. Although the present study is part of a research activity still in progress, this outcome emphasizes the possibility to obtain reliable fragility curves also considering smoothed spectra provided by national codes, if an adequate value of dispersion due to the record-to-record variability is properly considered, for instance by evaluating it a priori on natural record. The proposed procedure highlights the importance of the knowledge of the building characteristics in the derivation of consistent fragility curves. In this context, the presence of specific databases, such as the one developed within the CARTIS project, could represent an important support for the vulnerability assessment of existing buildings.

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