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Seismic Loss Estimation for an Old Masonry Building in Italy

Pietro Crespi
Assistant Professor, Dept. of Architecture Built Environment and Construction Engineering, Politecnico di Milano, Milan, Italy

Nicola Giordano
Research Associate, Dept. of Civil Engineering, University of Bristol, Bristol, UK

Giuseppe Frascaro
Structural Engineer, Milan, Italy

ABSTRACT: The last seismic events in Central Italy (L'Aquila 2009, Amatrice 2016) have demonstrated that the economic loss from physical damage strongly influence the community's recovery capability, especially when a relevant portion of the building stock is represented by unreinforced masonry (URM) constructions. As a matter of fact, URMs are recognized as the most vulnerable structures with respect to seismic forces. Furthermore, damage on masonry usually involves expensive and time-consuming repairing activities that can be carried out only by expert builders. Although these considerations are widely known among the Italian technical-scientific community, nowadays the social and political awareness about the problem is still quite low. One of the key aspects for an effective seismic risk mitigation is the analytical quantification of decision variables (e.g. monetary loss) to be shared with different stakeholders such as building owners, policy makers, insurance companies, etc. In response of this need, new assessment methodologies have been included in technical guidelines. In the present paper, the façade of a historic URM building located in the city center of L'Aquila is adopted as a case-study for the quantification of its seismic-induced economic average annual loss. In detail the Performance Based Earthquake Engineering (PBEE) approach proposed by the US FEMA P-58 and the simplified economic assessment methodology included in the Italian *Sisma Bonus* act are herein discussed and compared, pointing out the salient aspects of their application to URMs.

1. INTRODUCTION

Unreinforced masonry (URM) constructions represent a relevant portion of the global building stock and in Italy they account for 62.2% of the total inventory (Frankie et al. 2012). As observed after numerous earthquakes, these structures are intrinsically weak with respect to lateral seismic forces. Geometrical irregularities, low materials quality and ineffective wall-to-wall and wall-to-floor connections are just some of the reasons of their poor seismic response (D'Ayala and Paganoni 2011). From these considerations, over the last decades, engineers and researchers have focused their attention on the development of suitable seismic assessment approaches for URMs, mainly based on numerical modeling techniques e.g. the continuous finite element method (Lourenço 2002), the discrete element method (Lemos 2007) or the equivalent frame method (Roca et al. 2005). Regardless of the modeling methodology, usually the seismic assessment consists in evaluating the structural capacity of the building in the form of a force-displacement *pushover* diagram (Cattari et al. 2015; Silva et al. 2018). Subsequently, a capacity vs. demand check is carried out with well consolidated spectral-based approaches such as the Capacity Spectrum Method (CSM) (Freeman 1978) or the N2 method (Fajfar 1999) (currently included in the Italian Building Code (Ministero delle Infrastrutture e dei Trasporti 2008)). With these techniques, the outcome of the seismic assessment is fundamentally deterministic: as a matter of fact, the performance of the building is generally expressed in terms of maximum Peak Ground Acceleration (PGA) that the building can withstand without exceeding specific thresholds on displacements or internal forces.

Despite the practicality of these techniques, recent studies in the earthquake engineering field have pointed out the need of a more articulated definition of seismic performance (Moehle and Deierlein 2004; Porter 2003). Thanks to these works, remarkable advancements of the guidelines have been achieved in the last years. For instance, in the United States, the FEMA P-58 (Applied Technology Council 2012) includes the Performance-Based Earthquake Engineering methodology originally developed at the Pacific Earthquake Engineering Research Center at the University of California Berkeley (PEER-PBEE). The method consists of four analysis steps (hazard, structural, damage and loss analysis) and allows the calculation of the building performance in terms of probability of exceedance (PoE) of specific Decision Variables (DV) e.g. monetary loss, causalities, downtime (Günay and Mosalam 2013). Moreover, in 2017, the Italian Ministry of Infrastructure and Transportation released the *Sisma Bonus* act (Ministero delle Infrastrutture e dei Trasporti 2017) which reports a novel definition of 8 seismic performance-based risk classes (from G to A+). Specifically, the building risk class definition is based on a double level of assessment, namely the safety and the economic assessments.

In the present paper, the methodological approaches of these two guidelines are briefly discussed and consequently adopted for the estimation of the Average Annual Loss (AAL) of a case-study URM structure located in L'Aquila (Italy). AAL, also known as expected annual loss (AIR Worldwide 2013, RMS 2015), is a widely used statistic in catastrophe risk assessment and management.

2. THE PEER-PBEE METHODOLOGY

As anticipated in the introduction, the PEER-PBEE methodology involves four analysis steps (Porter 2003):

- *Hazard Analysis*. Consists of selecting proper ground motions whose Intensity Measures (IM) match a specific hazard level. A set of hazard levels are generally defined through PoE in the lifecycle of the structure (T_N).
- *Structural Analysis*. A numerical model of the structure is implemented. For each set of ground motions (defined in the hazard analysis) Nonlinear Time History Analyses (NTHA) are carried out. Subsequently, the probability functions of Engineering Demand Parameters (EDPs) for relevant damageable groups are derived. Uncertainties in the modeling input parameters can be also taken into account.
- *Damage Analysis*. The physical damage that affects the building is described through fragility functions. These curves indicate the PoE of a Damage Measure (DM) for any value of the EDPs.
- *Loss Analysis*. Consists of determining the DV associated to different damage levels. If monetary loss is adopted as DV, the damage repair costs and the Replacement Cost (RC) are estimated.

The last stage of the PEER-PBEE methodology is the calculation of the DV probability functions. Particularly, by combining the outcomes of the four analysis steps with the total probability theorem, a resulting loss curve is derived (Günay and Mosalam 2013). The curve reports the PoE of the DV values.

Thanks to the release of the FEMA P-58 (Applied Technology Council 2012) and the dedicated PBEE software PACT, in recent years the PEER-PBEE methodology has been increasingly adopted for the design of new facilities, but it is still infrequently employed for the assessment of existing URMs. Only recently, the methodology was used to carry out cost-benefit analysis for different retrofitting interventions on masonry buildings (Giordano et al. 2018).

3. THE SISMA BONUS ACT

As a consequence of the last tragic seismic events, in 2017 the Italian Government released the *Sisma Bonus* act (Ministero delle Infrastrutture e dei Trasporti 2017). This regulation incentivizes homeowners to invest in the seismic enhancement of their properties thanks to tax deductions up to 85% of the retrofitting cost. To take advantage from this tax relief the homeowner, with the help of an engineer, has to quantify the increase in seismic performance of his building in terms of risk class (8 classes from G to A+). Two assessments are required for the definition of the risk class:

- *Safety assessment.* By adopting the standard assessment procedures reported in the Italian Building Code (Ministero delle Infrastrutture e dei Trasporti 2008), consist of calculating the ratio between PGA_C (PGA related to the capacity of the building at the Life Safety Limit State) and the PGA_D (demand PGA prescribed by the Code at Life Safety Limit State). The ratio PGA_C/PGA_D is directly related to the risk classes as for Table 1.
- *Economic assessment.* Firstly, PGA_C for four Limit States (Service, Damage, Life Safety and Collapse) are calculated according to the Italian Building Code (Ministero delle Infrastrutture e dei Trasporti 2008). From these PGA_C, the annual frequencies of exceedance λ_C are estimated according to Eq. (1):

$$\lambda_C = \frac{1}{T_{rC}} = \frac{1}{T_{rD}(PGA_D/PGA_C)^{1/0.41}} \tag{1}$$

where T_{rC} and T_{rD} are the return periods related to capacity and demand respectively. Relying on a code-defined correlation between λ_C and economic loss ratio (i.e. economic loss/RC), a piecewise linear curve is constructed in the *λ vs. economic loss/RC* plane (Figure 1). The integral of the curve is the so called PAM factor which directly relates to the risk classes as indicated in Table 1. It is worth mentioning that the PAM factor is proportional to the AAL: as a matter of fact, it is possible to redraw the piecewise curve in an *economic loss/RC vs. PoE* plane by adopting the following formula (Iervolino et al. 2010):

$$PoE = 1 - e^{-\lambda_C T_N} \tag{2}$$

and then calculate the AAL as the ratio between the area under the new curve and the nominal life of the structure T_N.

Since any of the two assessment provides a different class of risk, the final class of the building is the minimum from the two estimations.

Table 1: Definition of risk classes for safety assessment and economic assessment according to Sisma Bonus act.

Safety assessment		*Economic assessment*	
PGA_C/PGA_D [%]	*Risk class*	*PAM [%]*	*Risk class*
≥ 100	*A+*	*≤ 0.50*	*A+*
[80 100)	*A*	*(0.5 1]*	*A*
[60 80)	*B*	*(1 1.5]*	*B*
[45 60)	*C*	*(1.5 2.5]*	*C*
[30 45)	*D*	*(2.5 3.5]*	*D*
[15 30)	*E*	*(3.5 4.5]*	*E*
< 15	*F*	*(4.5 7.5]*	*F*
		> 7.5	*G*

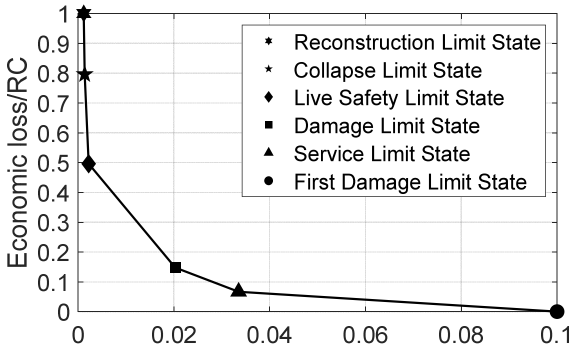

Figure 1: The piecewise linear curve defined in the Sisma Bonus act.

4. CASE STUDY

Economic loss assessment according to the PEER-PBEE methodology and the *Sisma Bonus* procedure was carried for the façade of an ancient

18th century URM building located in the city center of L'Aquila (Figure 2). The considered structure is characterized by three stories and general dimensions of 20 m (base) × 13.7 m (height). The thickness of the walls ranges between 100 cm (first story) to 76 cm (third story). For simplification purposes, the analysis was carried out considering the façade as a bi-dimensional system, disconnected with the orthogonal walls and not affected by out-of-plane damage as was actually observed during the post 6th April 2009 L'Aquila earthquake survey (Figure 3).

Figure 2: Masonry façade object of the study.

Figure 3: Damage pattern of the façade after the 2009 L'Aquila earthquake.

4.1. PEER-PBEE assessment

4.1.1. Hazard analysis

Nine different hazard scenarios with PoE of 0.02, 0.05, 0.10, 0.22, 0.30, 0.39, 0.50, 0.63 and 0.81 in 50 years are considered according to INGV (Italian Institute of Geophysics and Volcanology) indications (Stucchi et al. 2011). These scenarios are represented by a set of elastic acceleration response spectra reported in Figure 4.

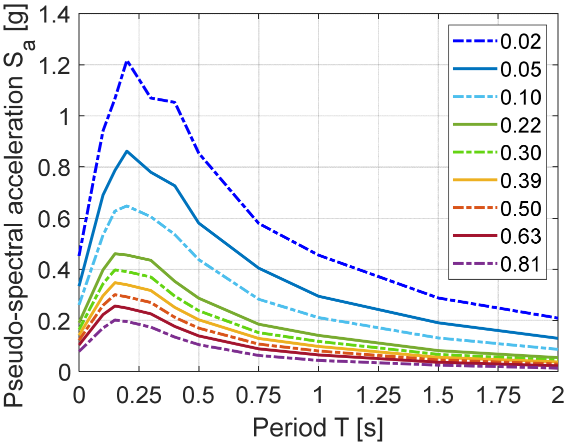

Figure 4: Target hazard spectra for different PoE.

From these spectra, 30 horizontal ground motions per scenario were selected using the software REXEL (Iervolino et al. 2010).

4.1.2. Structural analysis

The masonry façade numerical modeling was carried out according to the Equivalent Frame (EF) approach (Lagomarsino et al. 2013) and implemented in the *OpenSees* software platform (McKenna 2011). Mechanical characteristics of the masonry material were assumed according to the Italian Design Code (Ministero delle Infrastrutture e dei Trasporti 2009). The following modeling assumptions were considered in the development of the EF: (i) the nonlinear bending response of the piers was simulated adopting the *OpenSees* nonlinear force-based beam-column element (*forceBeamColumn*) with fiber discretization over the cross section; (ii) the shear damage potential of masonry piers was computed according to CNR-DT212 (Consiglio Nazionale delle Ricerche. 2012) and assigned to the force-based elements through the *OpenSees* section *Aggregator*; (iii) spandrels were modeled using elastic beam elements with reduced stiffness. It is worth mentioning that the modeling approach adopted for the piers was previously validated against experimental results by Raka et al (2015) and subsequently used for the numerical investigation of the non-linear response of perforated masonry walls (Siano et al. 2018). For these reasons, it was considered a reliable approach for the present study.

EF model of the façade was initially adopted for the execution of a NTHA using the ground motion record of the 6th April 2009 event. The results in terms of *base shear vs. top displacement* are reported in Figure 5. It can be observed that the structure remains stable, cycle after cycle, since it does not show phenomena of force degradation (softening) or diverging displacements. This numerical result seems in agreement with the light-to-moderate crack pattern reported in Figure 3.

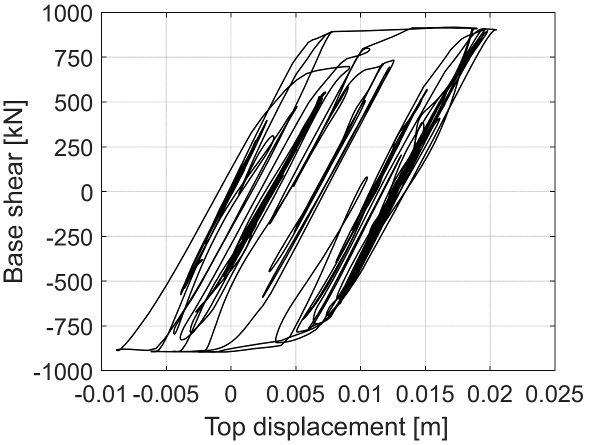

Figure 5:NTHA results in terms of base shear - top displacement envelope curve (L'Aquila earthquake ground motion).

Since the economic loss is mainly governed by the inter-story drift which generate damage in the masonry elements, one damageable group was defined for any story of the façade: *first story, second story and third story*. Maximum peak inter-story drift ratios (MIDRs) were then treated as the EDPs for the PBEE assessment.

NTHAs for the nine sets of ground-motions were executed using the *OpenSees* EF model. Subsequently, assuming a lognormal probability model, probability density functions of the EDPs and collapse probabilities were calculated as for Günay and Mosalam (2013).

4.1.3. Damage analysis

In absence of specific experimental fragility functions for the considered type of masonry, the definition of damage fragilities was carried out with numerical simulations. Particularly, three sets of fragility functions were derived by executing Nonlinear Static Pushover Analyses (NSPA) for any story of the façade (i.e. damageable group) by applying a horizontal force at the slab of the story while restraining the translation of the lower level. Consequently, from the force-displacement curve of the story, specific damage thresholds for light (DS1), moderate (DS2) and severe (DS3) damage were defined by adopting the methodology proposed by Rota et al. (2010). The corresponding MIDRs were then taken as the median values for the fragility functions while the dispersion (CoV) was assumed equal to 0.3 according to recent research works available in the literature (Frankie et al. 2012; Park et al. 2009; Rota et al. 2010). Figure 6 reports the resulting fragility functions where 1S, 2S and 3S means related to first, second and third story.

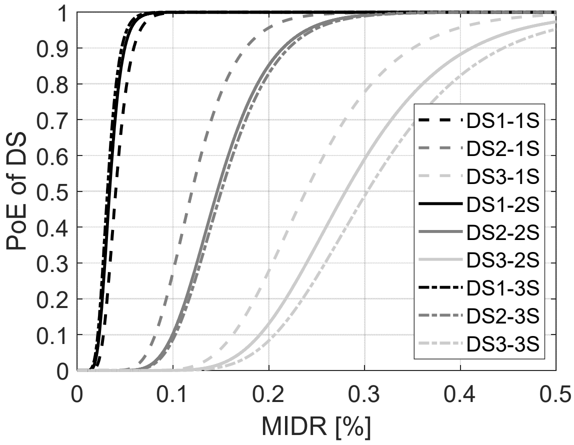

Figure 6: Damage fragility functions adopted in the PBEE analysis.

4.1.4. Loss analysis

The estimation of monetary loss was carried out adopting the official construction works pricelist of the Abruzzo Region (Regione Abruzzo 2018). In details, RC was estimated at €46,117 while repair costs for light, moderate and severe damage resulted to be 25%, 36% and 62% of the RC respectively. Loss functions related to each damage state were assumed with CoV = 0.1.

4.2. Determination of loss curves and AAL

As anticipated in section 2, loss curves for any hazard level are calculated by combining the results of the PEER-PBEE four steps analysis with the total probability theorem. In the present work the software tool PACT was used for the calculation of the loss curves (Applied Technology Council 2012). By computing the integral of each loss curve, one average loss value for each of the nine hazard levels (AL_H) was then obtained. Subsequently, in order to get a final AAL which does not depend from the hazard scenario, the couple of values, AL_H and corresponding hazard PoE, were reported into a diagram (Figure 8). The integral of the resulting multilinear curve divided by the nominal life T_N is the AAL of the structure which resulted in 187.12 €/yr for the considered case study.

4.3. Sisma Bonus assessment

Estimation of the economic loss was then carried out with the *Sisma Bonus* procedure. Firstly, a NSPA of the EF described in 4.1.2 was implemented to extract a force-displacement curve of the façade. Particularly, displacement thresholds related to Service, Damage, Life Safety and Collapse Limit States have been defined on the capacity curve of the structure as for Rota et al. (2010) (Figure 7).

Subsequently, as reported in section 3, PGA_C are estimated according to the Italian Building Code (Ministero delle Infrastrutture e dei Trasporti 2008) while corresponding λ_C and PoE are calculated with Eqs. (1) and (2) respectively. Lastly, thanks to the correlation between limit states and economic loss (see Table 2) provided by the *Sisma Bonus* act, a piecewise linear curve in the same plane of the PEER-PBEE multilinear curve is represented (Figure 8).

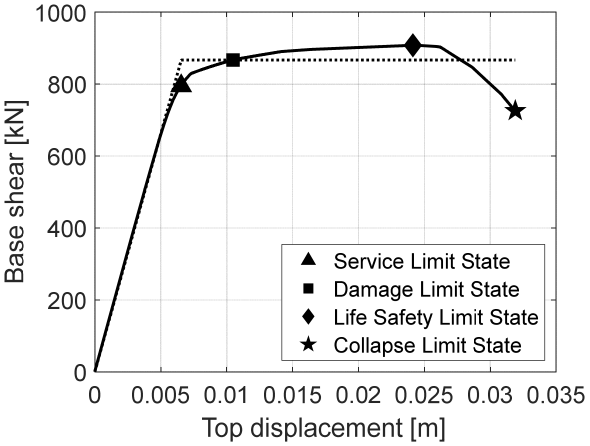

Figure 7: Definition of the displacement thresholds for different limit states.

Table 2: Correlation between limit states and economic loss according to Sisma Bonus act.

Limit state	*Economic loss / RC*	*Limit state*	*Economic loss / RC*
Reconstruction	*100%*	*Damage*	*15%*
Collapse	*80%*	*Service*	*7%*
Life Safety	*50%*	*First Damage*	*0%*

Once again, the integral of the diagram divided by the lifecycle of the structure T_N is the AAL which result in 231.50 €/yr for the considered case study.

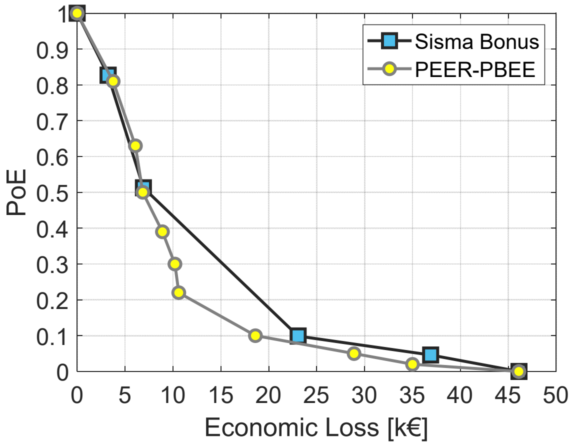

Figure 8: Comparison between PEER-PBEE and Sisma Bonus loss assessments.

5. CONCLUSION

Nowadays, quantifying the potential economic loss from earthquake hazard is becoming crucial for the implementation of effective risk mitigation actions. In the Italian context, this results in an increasing need to properly assess existing masonry constructions since they represent a large portion of the national building stock.

Starting from these considerations, this paper presented the seismic monetary loss estimation of an URM façade by adopting the PEER-PBEE methodology (US FEMA P-58 approach) and the simplified Italian *Sisma Bonus* act procedure. The assessment analysis outcomes showed that the final loss curves are in good agreement with a slight difference in the region between PoE = 0.1 and PoE = 0.5 due to the lower number of scenarios considered in the *Sisma Bonus* method. In terms of AALs, the PEER-PBEE provide a lower estimation with respect to the *Sisma Bonus* assessment ($\mathrm{AAL}_{\mathrm{PEER\text{-}PBEE}} = 0.81 \times \mathrm{AAL}_{SismaBonus}$) which shows that the latter technique is simplified but conservative. These results should be considered valid within the main assumption of the study (i.e. the façade is considered as an independent structure) and could be furtherly improved by repeating the loss assessment for the whole building. Lastly, it is worth mentioning that the higher computational cost of the PEER-PBEE methodology could be surely justified when dealing with complex and high-value constructions (e.g. monumental structures) since better estimation of AAL could, for example, decrease their premium insurance rate.

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