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Probabilistic seismic performance of masonry towers: General procedure and a simplified implementation

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ABSTRACT

A procedure for the probabilistic assessment of the seismic performance of masonry towers is developed within the general PEER framework. The ingredients identified for the whole procedure are the Intensity Measure (IM), the mechanical model, the seismic procedure, the Engineering Demand Parameter (EDP), the uncertain mechanical parameters, and the probabilistic method. For each one, a choice suitable for masonry towers is proposed. A tower is modeled as a geometrically nonlinear Timoshenko beam with no-tensile and limited-compressive strengths. The reaching of the ultimate compressive strain is assumed as main failure criterion. Pushover analyses are carried out and a performance measure based on the seismic displacement capacity and demand is used as EDP. The conditional probability of exceedance of the EDP given the peak bedrock acceleration, used as IM, is computed through Monte Carlo simulations by considering as random variables the mechanical parameters representative of inertia, stiffness, strength, and ductility of the masonry. The calculations are then developed with reference to a case study. The dispersion of the displacement capacity is recognized as the main source of uncertainty. As to the mechanical parameters, the compressive strength and the strain ductility play the most critical roles, as also highlighted by a sensitivity analysis. These parameters are the most uncertain as destructive tests, usually not allowed in historical monumental buildings, would be required for their assessment. The effects of static load patterns for nonlinear static analysis and the comparison with incremental dynamic analysis are also briefly discussed.

1. Introduction

The comprehensive probabilistic assessment of the seismic performance of a structure requires the introduction of many sources of uncertainty. Geometry, material properties, and load characteristics are directly observable and then represent basic random variables. The choice of the probabilistic distributions used to model the basic random variables represents another source of uncertainty. The models that provide the derived variables (e.g., seismic response, damage, cost variables) are also uncertain. Statistical errors arise from the estimation of the parameters of the previous probabilistic and physical models obtained by fitting experimental data. Other errors involve the measured data from which the parameters of the probabilistic and physical models are estimated. Finally, uncertainties in the derived variables result from computational procedures, numerical approximations, and truncations.

Sources of uncertainty can be classified as aleatory or epistemic [1]. Aleatory uncertainties are those that cannot be reduced with the present knowledge by gathering more data or by refining models. Conversely, an uncertainty is said to be epistemic, when more data or more sophisticated models could be used to reduce it.

According to the previous definitions, intensity and record-to-record variability of the ground motion, which define the Intensity Measure (IM) in the PEER (Pacific Earthquake Engineering Research) approach [2], are commonly treated as aleatory uncertainties (since their reliable predictions are far away to be accomplished). For an existing structure, geometry (e.g., sizes of the cross-section, tilt due to ground settlements) and material properties (e.g., mass density, strengths, elastic moduli, ductility) are classified as epistemic uncertainties (since more accurate information about such variables could be obtained by measurements and laboratory tests on specimens taken from the structure).

In the literature, no study systematically takes into account all the above sources of uncertainties. Several studies (e.g., [3,4]) regard the effects on Engineering Demand Parameters (EDPs) of ground motion intensity and profile (record-to-record variability), which are usually recognized as the main source of uncertainty in the prediction of seismic response [5]. Only in recent years the effects of modeling uncertainties on EDPs have been investigated

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for common structures (e.g., reinforced concrete shear-walls or steel-frame buildings) by sensitivity [6,7] and propagation analyses [8–12]. The conclusions about the influence of the modeling parameters on EDPs are generally valid for the considered case studies and unlikely they can be extended to other cases. A few papers deal with the probabilistic vulnerability assessment of masonry buildings (e.g., [13–16]) or of slender structures such as steel chimneys (e.g., [17]). Masonry towers have been subject of several studies [18–29], although rarely of probabilistic ones. In [30], a probabilistic analysis of the vulnerability of a masonry tower is performed by accounting for the uncertainties of the material properties and their spatial variability, but only gravity loads are considered; in [31] an approximate probabilistic method is applied by assuming *a priori* lognormal distributions with assigned coefficient of variation for the EDP and estimating its median by a single time-history analysis.

The present work deals with the propagation of both epistemic uncertainties, arising from the material properties, and aleatory ones, arising from the earthquake intensity, on the EDP, whose distribution is derived from those of the mechanical parameters and convoluted with the hazard curve to obtain the mean annual frequency of EDP. The ingredients of the whole procedure are identified in the definition of the intensity measure and of the engineering demand parameter, in the choice of the mechanical model, the seismic procedure, the random variables and their distributions, and the probabilistic method. For each element, possible choices suitable for masonry structures are briefly discussed. The procedure is then applied to a case study for which complete numerical calculations are carried out.

In the next section, the seismic loss estimation framework proposed by the PEER Center [2,9] is summarized and particularized for the application to the seismic risk of masonry towers. The first two rings in the chain of the PEER framework, concerning the hazard and the vulnerability, are developed to obtain the mean annual frequency of exceedance of the EDP.

In Section 3, the procedure for estimating the performance index (EDP) of the tower is described, including the adopted mechanical model, the seismic procedure, and the choice of a suitable performance measure. All the ingredients are chosen so that the main physics of the problem is reproduced and the whole procedure is kept as simple as possible.

In Section 4, the procedure is used to evaluate the mean annual frequency of the EDP for an idealized scheme of the medieval "Torre Grossa" in San Gimignano (Tuscany, Italy). The town, included in UNESCO World Cultural Heritage list, posses seventeen monumental towers of a homogeneous typology, with hollow rectangular cross-section, approximately constant along the height, and small openings. Similar towers are also present in other European sites. Statistics of the performance index (EDP) of the tower are determined through Monte Carlo simulations by considering uncertain mechanical parameters, as partially outlined in [32].

In Section 5 some remarks on the whole procedure and on the specific case study are reported.

2. PEER framework

The cost estimation chain proposed by PEER Center represents a classical framework to determine seismic risk. The costs, commonly termed Decision Variable (DV), are assessed by deconvolving the structural Damage Measure (DM), the Engineering Demand Parameter (EDP), and the ground-motion Intensity Measure (IM) as intermediate variables. By repeatedly applying the total probability theorem one obtains [33]

$$\lambda(\mathbf{DV}) = \iiint G(\mathbf{DV}|\mathbf{DM})|dG(\mathbf{DM}|\mathbf{EDP})|\,|dG(\mathbf{EDP}|\mathbf{IM})|\,|d\lambda(\mathbf{IM})|, \quad (1)$$

where the four random variables represent the ground motion intensity (**IM**), the structural response (**EDP**), the damage (**DM**) and the corresponding cost (**DV**); $\lambda(\mathbf{IM})$ is the mean annual rate of exceeding a given $\mathbf{IM}$; $G(\mathbf{X}|\mathbf{Y})$ is the complementary cumulative probability function of **X** conditioned on a given level of **Y**. In the general case in which the variables are vector valued, λ and G are also vectors of functions, whose elements are the mean annual frequencies and conditional probabilities of exceedance.

This work cover the first two rings of the cost estimation chain. The hazard term is derived in a simplified manner from the literature. The vulnerability term is assessed by estimating the statistics of the structural response for assigned values of the seismic IM.

A nonlinear static seismic approach is adopted, so that the peak bedrock acceleration a_g can be used as the only measure of the earthquake intensity, $\mathbf{IM} = \{a_g\}$, being the record-to-record variability incorporated in the seismic response spectra. For more sophisticated analyses, such as incremental dynamic analysis [3], more efficient IMs could be adopted [34]. We consider as EDP the index I_d, defined in Section 3.3, depending on the displacement demand and capacity, $\mathbf{EDP} = \{I_d\}$. For now, it is sufficient to consider I_d as a measure of the damage of the structure, ranging from zero (undamaged structure) to one (collapsed structure). The mean annual frequency of exceeding I_d is

$$\lambda_{I_d}(I_d) = \int_0^\infty G(I_d|a_g)\left|\frac{d\lambda_{a_g}}{da_g}\right|da_g, \quad (2)$$

where $G(I_d|a_g)$ is the probability of exceeding a certain I_d, given a peak bedrock acceleration with intensity a_g, and the seismic hazard λ_{a_g} is the mean annual frequency of exceeding a given value of a_g.

3. Procedure for estimating the probabilistic EDP

We develop in detail the vulnerability ring of PEER chain (Fig. 1) and evaluate the integral of Eq. (2) by assuming a simplified scheme for the hazard-ring. In a deterministic case, the peak bedrock acceleration a_g, i.e. the IM, and the mechanical parameters of the structure are taken as input and the measure of seismic performances I_d, i.e. the EDP, is given as output. To account for the structural uncertainties, Monte Carlo simulations with randomly varying structural parameters and fixed values of a_g are performed. In such a way, the mean annual frequency of exceedance of I_d for a given a_g is obtained. By repeating the Monte Carlo procedure for different values of a_g, the conditional probability of exceedance of I_d given a_g, namely $G(I_d|a_g)$, is obtained at discrete points. Such conditional probability is the final result of the probabilistic vulnerability assessment.

The overall procedure can be schematized as follows:

- For each Monte Carlo step:
  - A set of mechanical parameters is generated from their probability distributions.
  - A pushover analysis of the structure, using the selected mechanical model, is performed, resulting in a capacity curve (this step hides two further nested loops of the nonlinear-static incremental–iterative procedure).
  - The displacements at elastic limit and at failure are determined during the pushover analysis.
  - The period and the yielding force of the equivalent single degree-of-freedom (SDoF) system are derived from the capacity curve.
- Arrays collecting the elastic and ultimate displacements, the periods and the equivalent yielding forces are stored.
- The corresponding PDFs are estimated.
- For each considered value of a_g:
  - The response spectra are computed.