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Seismic Vulnerability Assessment of Ancient Masonry Building: an Experimental Method

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Abstract This paper presents a review of the methods for seismic vulnerability assessment, together with an experimental method based on shaking table testing. This method is applied to a Portuguese masonry building typology with stone walls and timber floors, subjected to increasing earthquake damage. Traditional-like materials and techniques are used in the building. The vulnerability curves are presented and the damage indicator is correlated with the crack patterns and EMS 98.

Keywords: Seismic vulnerability, ancient masonry building, shaking table test

Introduction

For a long time seismic engineering has focused on reinforced concrete structures, particularly on their design procedures. In the recent decades the study of the vulnerability of ancient buildings is receiving much attention due to the increasing interest in the conservation of the built heritage and the awareness that life and property must be preserved. Even in seismic areas, unreinforced masonry structures represent the major part of the building stock. This building typology was often non-engineered or not designed with reference to any particular code and it is likely to possess a high seismic risk.

This paper presents a review of the methods for seismic vulnerability assessment and its classification. An experimental method to estimate the vulnerability curves, based on previous experience from the National Laboratory for Civil Engineering (LNEC), is presented. This method includes shaking table tests and is based on the evaluation of the natural frequencies of the mock-up building through a series of seismic tests with increasing input excitations. Finally, the experimental method is applied to a masonry building typology ("gaioleiro" buildings), which probability presents the highest seismic vulnerability of the housing stock of Portugal. The damage indicator, obtained through decreased of the frequencies, is correlated to the crack patterns and EMS 98 (Grünthal 1998).

Seismic Vulnerability Assessment

Seismic vulnerability assessment can be applied to housing, structural elements of a building (columns, piers, tower), cultural heritage buildings (monuments), essential facilities (hospitals, fireman´s headquarters, police stations), infrastructure (roads, water, power grids) and any other type of buildings (e.g. schools or concert halls). Taking into account this diversity and the objectives pursued, different methods to assess the seismic vulnerability can be used. Moreover, different classifications of methods have been proposed.

Corsanego and Gavarini (1993) divided the approaches developed in Italy to assess the seismic vulnerability in three main methods: (a) typological, (b) mechanistic and (c) hybrid.

The first type of methods is based on the definition of building typologies, taking into account the construction technology (materials, geometry, type of horizontal diaphragms, connections between the elements, etc.), and the vulnerability is assessed through damage caused in real earthquakes and is expressed in probabilistic terms for each typology. Mechanistic methods assess the seismic vulnerability through theoretical mechanical models of the buildings. At territorial (regional) level, simplified analytical models of the structure schemes can be used. In the hybrid methods quantitative (e.g. numerical analyses) and qualitative (e.g. experts' opinions) information on the building are combined to assess the seismic vulnerability.

Besides these three main groups, Corsanego and Gavarini (1993) proposed other types of classification of assessment methods for seismic vulnerability taking into account the kind of measure used to define the seismic vulnerability (quantitative and qualitative methods), the sort of results that emerge (direct, indirect and conventional methods) and prevalent source of knowledge (statistical, analytical and subjective methods).

Palacios (2004) presented a research about the methods of seismic vulnerability assessment, in which two main methods were highlighted: probabilistic methods (observed vulnerability) and the deterministic methods (predicted vulnerability).

The probabilistic methods are mainly used to study a group of buildings and are based on the statistic data of past earthquake damage. However, depending on the source of the statistic data, four sub-groups can be defined:

- Empirical methods, which are based on observed earthquake damage data.
- Judgment methods, which are based on experts' opinions.
- Analytical methods, which are based on analytically simulated damage data.
- Hybrid methods, which are based on combinations of different sources.

On the other hand, deterministic methods are mainly used to assess the seismic vulnerability of single structural units and they refer to the performance point of existing structures, before and after strengthening, and to the design of new structures.

Recently, Sousa (2006) presented the methodologies for seismic vulnerability assessment in a chart (Fig. 1), being the methods divided in two main groups: mechanistic and statistic/empirical.

The first group (mechanistic methods) includes the analytical methods to assess the seismic vulnerability at individual level, using procedures similar to those used in structural analysis, and at regional level, through simplified mechanistic models, as the capacity spectrum method (ATC 1996).

The second group (statistic/empirical methods) refers to methods based on the damage statistical data observed in real earthquakes and/or expert opinion. These methods are usually used to assess the seismic vulnerability of large samples of buildings. Sousa (2006) divided this group in three classes: (a) methods based on the data collection of damage caused by earthquakes, in which the vulnerability is assessed by building typologies (Braga et al. 1982), (b) indirect and rating methods, in which the capacity of the buildings to resist seismic action is evaluated first, and its correlation with damage is done afterwards (Barbat and Pujades 2004) (c) hybrid methods, in which the characteristics of the two different methods are combined (Giovinazzi and Lagomarsino 2003).

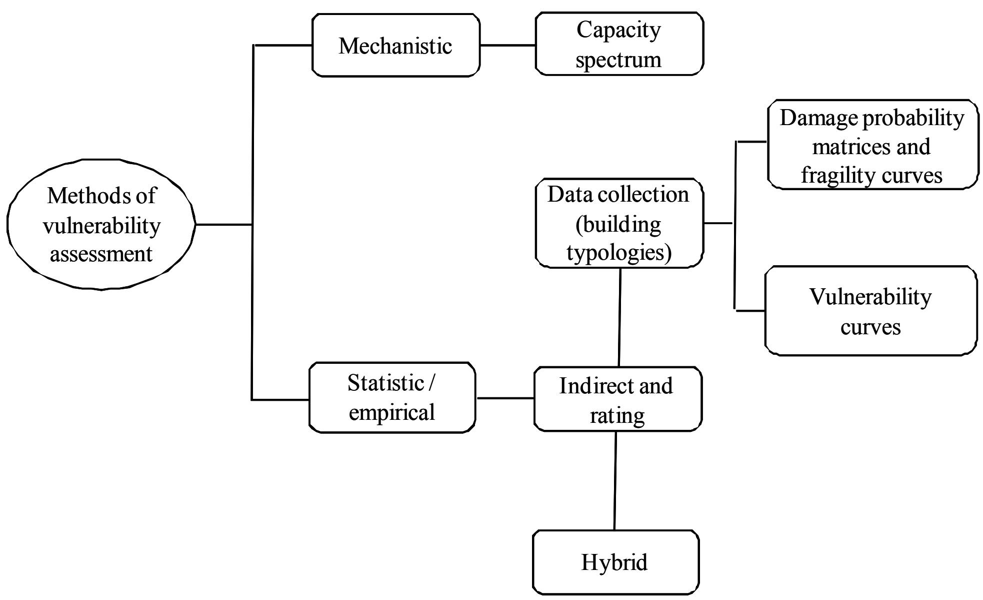


Figure 1: Methodologies of seismic vulnerability assessment. (Adapted from Sousa 2006)

Estimation of Experimental Vulnerability Curves

The methodology for seismic vulnerability assessment through experimental tests is usually based on the identification of the dynamic proprieties of the mock-ups along a series of seismic tests with increasing input excitations (Degée et al. 2000, Bairrão and Falcão 2009, Candeias 2009). The dynamic properties give inherent information of the mock-up and its evolution is related to the damage induced by a given seismic input. The procedure involves cycle, pseudo-dynamic or shaking table tests to induce the seismic input and characterization tests to identify dynamics properties.

Shaking table tests, which are the subject of this paper, consist of imposing artificial accelerograms compatible with a hazard scenario or real strong earthquakes. In this type of tests, usually, it is possible to study the seismic performance of entire structures in real and reduced scale imposing the seismic series at structure base level in one to three directions, depending of the facility characteristics. Due to costs involved, the mock-up does not have the same initial conditions, i.e. before the application of the seismic input the mock-up presents (cumulative) damage, with exception of the first one. The damage observed in the nominal test i is not only caused by the seismic action applied in the particular test, but it is also related with the excitation induced in the previous seismic tests. Thus, the damage indicator of the test i must be associated to the energy/intensity accumulated, which is a seismic action parameter obtained through the integration of the acceleration series. The characterization of the input series through the peak values must be adjusted taking into account the test planning. Eq. 1 presents a proposal to determine the equivalent PGA (PGAeq) through the use of the energy concept, in which Eac is the accumulated energy until the actual test i; Enoi and PGAnoi are the nominal energy and peak ground acceleration in the test i, respectively. This proposal does not take into account that the response of the mock-up (damage) observed in the test i is also a function of its initial conditions. It is noted that mock-ups with different initial conditions have different energy dissipation capacities.

$$PGA_{eq_i} = \left(\frac{E_{ac_i}}{E_{no_i}} \right)^{0.5} PGA_{no_i} \tag{1}$$

The dynamic properties of the structures can be identified through ambient and forced vibration testing (Krämer et al. 1999, Mendes et al. 2010). In the shaking table tests, usually, the evolution of the dynamic properties of the mock-ups is based on the experimental transfer functions (e.g. Frequency Response Function, FRF) evaluated in characterization tests (forced vibration) carried out before the first seismic test and after each of the seismic tests (Fig. 2).

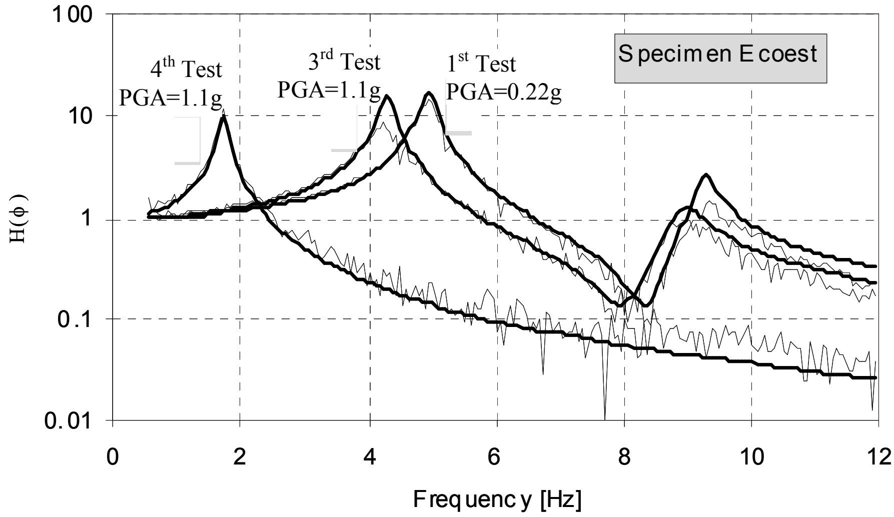


Figure 2: Experimental and analytical transfer functions for tests with increasing input signals. (Coelho et al. 2000)

The reduction of the natural frequencies is related to the stiffness variation and, consequently, to the evolution of the damage. Eq 2 presents a simplified damage indicator dk,i based on the variation of the natural frequencies fk,i (fk,0 is the natural frequency of the mode shape k before the application of the first seismic test). This damage indicator assumes that the global mass of the mode shape k does not change meaningfully in the different tests and presents different values for each mode shape. It is noted that the results of the seismic tests (maximum displacement, drifts, crack patterns) can also be used to defined damage indicators.

In this procedure, the experimental vulnerability curves of the mock-ups are defined relating the seismic excitation parameters (energy/intensity accumulated, PGAeq) and the damage indicator d.

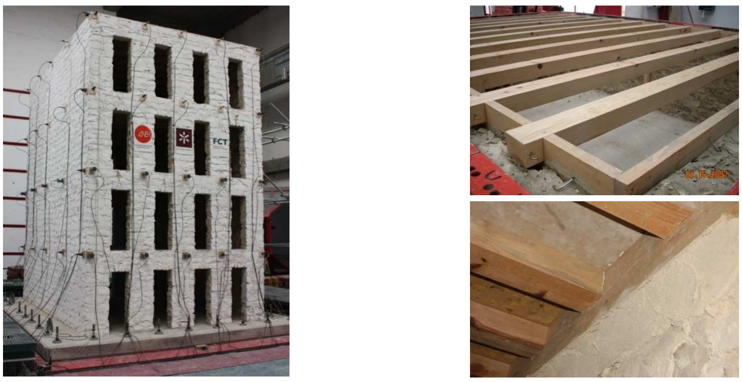
$$d_{k,i} = 1 - \left(\frac{f_{k,i}}{f_{k,0}} \right)^2 \qquad (2)$$

Case Study: "Gaioleiro" Buildings

In the study of the seismic behavior of the "gaioleiros" buildings, the experimental method to estimate the vulnerability curves is now applied. The prototype has four stories high, masonry walls and flexible floors (Mendes and Lourenço 2010). Due to the size and payload of the shaking table, the mock-up (Fig. 3) was built using a 1:3 reduced scale, taking into account the Cauchy's law (Carvalho 1998). The seismic tests were performed at the LNEC shaking table by imposing accelerograms compatible with the design response spectrum defined by the Eurocode 8 (EN 1998-1 2004) for Lisbon, with a damping ratio equal to 5% and a type A soil (rock). The accelerograms were imposed with increasing amplitude in two uncorrelated orthogonal directions that should present approximately the same PGA_{no}. Due to experimental difficulties in the tests, the PGA_{no} in the longitudinal direction is about 1.3 times of PGA_{no} in the transversal direction.

In the first dynamic characterization of the mock-up (before the first seismic test) 11 mode shapes were estimated (Fig. 4). The transversal modes are mainly associated to the global behavior of the mock-up and were clearly identified (1st, 5th and 10th modes). The longitudinal modes are mainly related to the local behavior of the façades and can be distinguished by the type of curvature (single, double and triple). Due to the presence of two peaks very close in the FRF´s, the 2nd mode of the North façade was not clearly identified (6th and 7th modes). A distortional mode of the floors (2nd mode) and a combined mode (8th mode) were also identified.

Due to the damage that occurred in the intense seismic tests, it was not possible to continue estimating the 11 mode shapes along the tests. In fact, only the three transversal modes and the first two longitudinal modes were adequately estimated in all characterization tests (Figs. 5a and 5b). The average MACs (Allemang 2003) of the first and second transversal modes are equal to 0.95 and 0.77, respectively. The others mode shapes, mainly the longitudinal modes, present very low MACs, due to the damage concentration of the façades occurred along the seismic tests (Figs. 5c and 5d).



(a) (b)

Figure 3: Mock-up building: (a) general view; (b) details of the floors

Figs. 5a and 5b present the vulnerability curves of the mock-up in the transversal and longitudinal directions, respectively. The highest damage indicator d is equal to 0.86 (1st longitudinal mode). In the final characterization test, the frequency of the 1st transversal mode remains equal to the previous test (d=0.80). Probably, after the third seismic test, the 1st transversal mode is, mainly, related with the stiffness of the gable walls connected by floors. Although useful for comparing mock-ups, the damage indicator d does not give detailed information about cracking occurring in the masonry walls. Thus, this damage indicator should be analyzed taking into account also the cracks patterns (Figs. 5c and 5d). The first, second, third and fourth cracks patterns are related with the grade 1, 2, 3 and 4 presented in the EMS 98. In the last crack pattern, serious cracking of the lintels and piers was obtained.

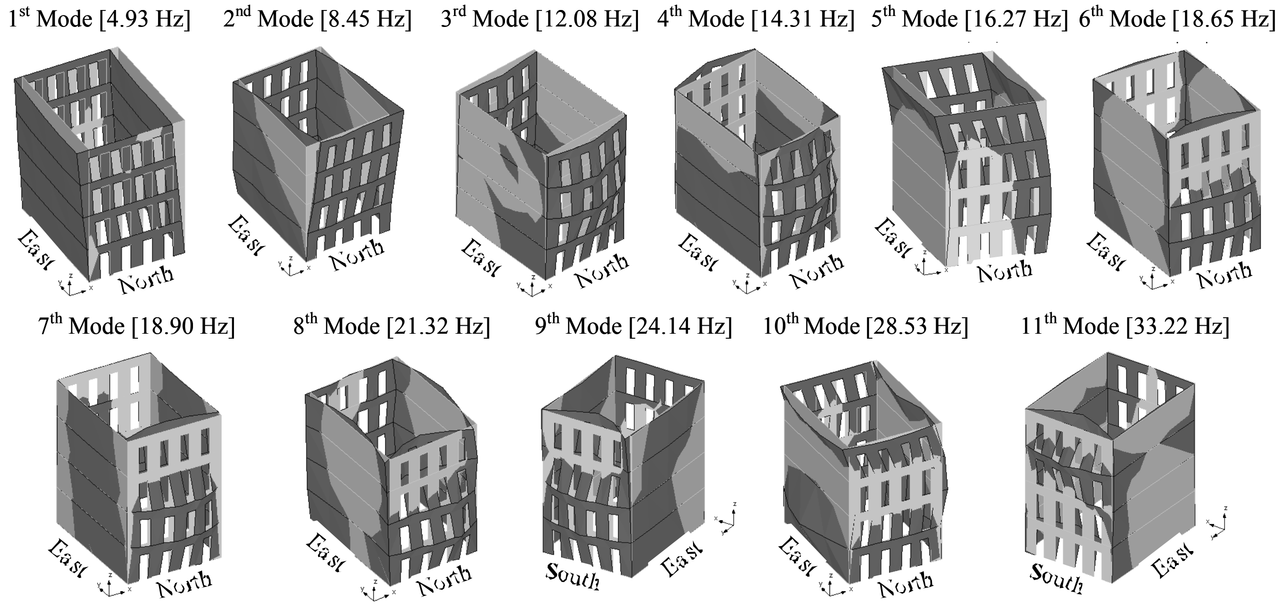


Figure 4: Mode shapes of the first dynamic identification of the mock-up (before testing).

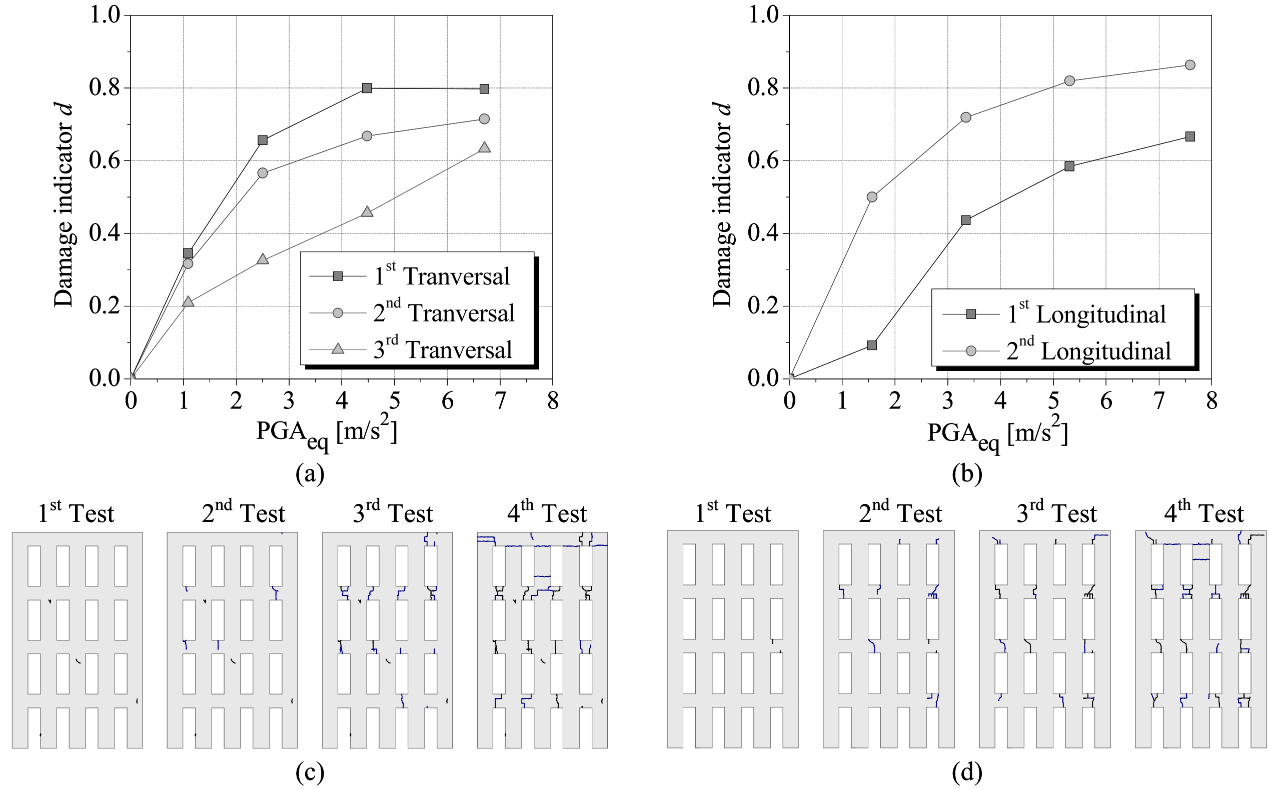


Figure 5: Vulnerability curves in the (a) transversal and (b) longitudinal direction and crack pattern of the (a) North and (b) South façade of the mock-up

Conclusions

This paper presents an experimental method to estimate the seismic vulnerability curves, which was applied to a Portuguese masonry typology ("gaioleiros" buildings). The shaking table tests allowed concluding that the mock-up presents substantial to heavy damage (grade 3 of the EMS 98) for the code seismic action (type A soil). The vulnerability curves will be used to assess the efficiency of strengthening techniques. The assessment of seismic vulnerability of the "gaioleiros" buildings should take into account the dispersion in the typology. Thus, the future works should involve the preparation/calibration of numerical models and a parametric study, assuming as variables, namely, the type of soil, the material properties and the number and the stiffness of the floors.

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