Seismic vulnerability assessment based on vibration data at the city-scale

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SUMMARY:
The dynamic behaviour of existing buildings is hard to assess at the scale of a city. The most critical parameters necessary to predict the response of a structure under earthquake may be extremely uncertain using current vulnerability methods. However, ambient vibration recordings in buildings provide the actual dynamic behaviour of buildings under low strains. Even if they may change under higher loads, these values provide a linear starting point relevant at least for the prediction of slight damages. This paper provides models based on frequencies, mode shapes and damping, extracted from ambient vibrations, for each class of structure for vulnerability assessment. A complete methodology to derive fragility curves for slight damage, including a discussion on sources of uncertainty and variability is proposed and applied to the city of Grenoble, using ambient vibration tests from 60 buildings. A site-specific earthquake scenario, taking into account local site conditions, is considered, corresponding to a M_L=5.5 earthquake at a distance of 15km simulated using Empirical Green's Function method.

Keywords: vulnerability assessment, ambient vibration tests, slight damage grade

1. INTRODUCTION

Seismic vulnerability assessment for loss estimation, i.e. at least at the city-scale, is an extremely difficult task involving: 1) Building inventory and classification 2) Modelling of each class of buildings 3) Estimation of fragility curves including all uncertainty sources. The trend in the literature toward such mechanical approaches is driven by the more and more accurate ground motion models provided by seismologists. In these models accounting for the effect of local geology on ground motion, part of the variability of observed ground motion is explained and should therefore be reflected in vulnerability models in order to better explain observed damage. The seismic demand on structures is therefore extremely dependent on their resonance frequencies and damping ratios that should be accurately represented. Mechanical models currently used in the literature are not stressing on this aspect because they are based on design procedures, therefore for simple, very smooth, code-based seismic spectra. Observed earthquake response spectra show large amplitude variations along the frequencies, especially due to resonance of sedimentary layers.

Capturing accurately the resonance frequencies and damping ratios of existing structures is therefore critical in vulnerability assessment. A simple way to extract resonance frequencies of structures is to use ambient vibration recordings (e.g. Michel et al., 2008). Modal parameters (frequencies, damping and modal shapes) obtained from ambient vibrations are valid on a wide range of amplitudes (e.g. Michel et al., 2008, 2010a). However, under earthquake loading, frequency drop due to elastic opening of existing cracks and further on damage, was observed by many researchers (e.g. Michel and Guéguen, 2010; Michel et al., 2011a). In classical mechanical approaches, to account for this phenomenon, the "cracked" elastic modulus of concrete or masonry is generally used, implying a basic decrease of 50 to 70%. If the "cracked" stiffness is difficult to retrieve for existing buildings, even the uncracked one is not obvious due to unknown initial material stiffness, approximate geometry and eventually effects of ageing and past damage. The ambient vibration modal properties are therefore good linear starting points for accurate vulnerability models. In this paper, we assumed that these parameters are valid up to the slight damage grade. Extension of the method to higher damage grade is discussed in the conclusions.

The first part of this paper describes the instrumentation effort performed in Grenoble to record ambient vibrations in many buildings of different types. The second part describes the model used and the derivation of fragility curves and finally the application to the city of Grenoble, France. This work is more extensively described in Michel et al. (2012). This paper provides a critical view of the method in the light of more recent work especially providing future directions for enhancements.

2. AMBIENT VIBRATION DATA COLLECTION AT THE CITY SCALE

The classification of buildings in Grenoble was performed in Guéguen and Vassail (2004) and a simplified version can be found in Michel et al. (2012). A large instrumentation effort was made to record ambient vibrations in many buildings representative of different building classes in Grenoble. Full-scale analysis was performed in 60 buildings allowing to derive resonance frequencies, damping ratios and modal shapes. A Cityshark II (Chatelain et al., 2000) station allowing to digitize data from six 3-component sensors. Lennartz 3C-5s seismometers were used for these measurements. 15 min recordings were performed with at least one sensor per story. Such full-scale recordings are necessary to understand the structure dynamics and therefore interpret the extracted modes.
The Frequency Domain Decomposition (FDD, Brincker et al., 2001) was used to process the recordings. This method allows to take the most of the simultaneous recordings by performing a singular value decomposition of the power spectral density matrices. This processing allows to separate modes, even close.

The data collected allowed to study the resonance frequencies (Michel et al., 2010b) and the modal shapes (Michel et al., 2012) of existing buildings of the different classes. As an example, the difference of behaviour of masonry structures with wooden or stiff floors was clearly shown (Fig. 1): buildings with stiff floors have a nearly triangular modal shape, mixing bending and stiffness behaviour, whereas buildings with wooden floors behave in bending only. This bending behaviour implies a lower inter-story drift at the ground floor compared to a triangular shape, for the same top displacement. The interaction between floors and walls, known as frame effect, is difficult to quantify in analytical methods. Experimental modal shape is therefore also of critical interest for the vulnerability assessment.

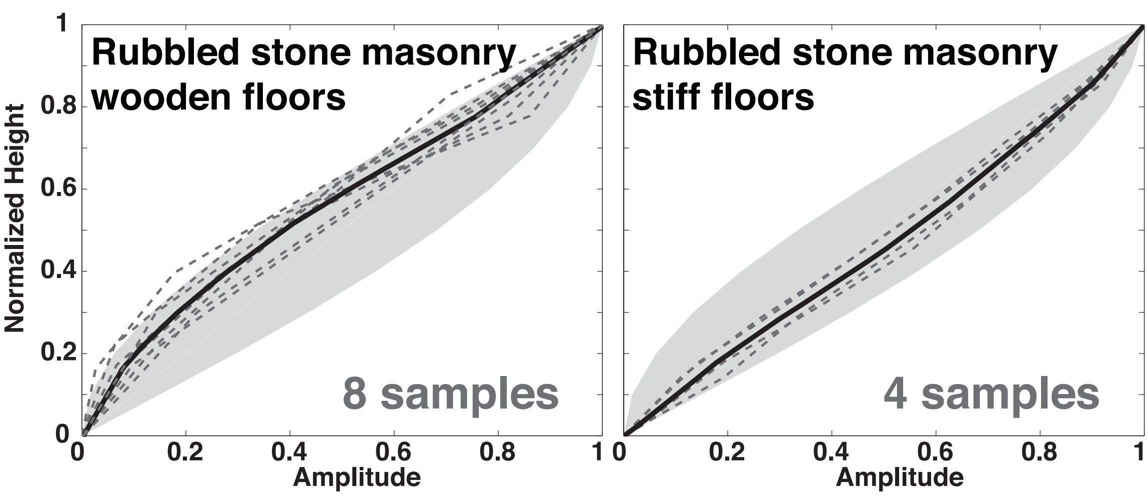

Figure 1. Modal shape of the fundamental mode for stone masonry structures with wooden and stiff floors. Black thick line is the average of the class. Grey zone represents the theoretically possible range of behaviour.

In the future, new remote sensing technique should allow a city-scale mapping of the resonance frequencies (Guéguen et al., 2010), therefore increasing the amount of data for this method.

3. DERIVATION OF FRAGILITY CURVES

3.1. Modelling

To perform a vulnerability assessment, a model of each class of buildings has to be proposed. In this work, we are using a 1D dynamic elastic model based on the collected modal parameters. Michel et al. (2008, 2010) remarked that only a hypothesis on the relative values of the masses at each floor (e.g. equal masses) was needed to compute the response of a multiple degree-of-freedom system with known resonance frequencies, damping and modal shapes to a ground motion. The displacement response at each story {U(t)} to a ground motion displacement $U_s(t)$ can be written as follows:

$$\{U(t)\} = [\phi]\{y(t)\} + U_s(t) \tag{3.1}$$

$$\forall j \in [1, N] \quad \begin{matrix} y_j(t) = \frac{-p_j}{\omega'} \int_0^t U_s''(\tau) e^{-\xi_j \omega_j (t-\tau)} \sin\big(\omega'(t-\tau)\big)\, d\tau \\ with \;\; \omega'^2_j = \omega_j^2 (1 - \xi_j^2) \end{matrix} \tag{3.2}$$

$$p_j = \frac{\{\phi_j\}^T [M]\{1\}}{\{\phi_j\}^T [M]\{\phi_j\}} = \frac{\sum_{i=1}^N \phi_{ij}}{\sum_{i=1}^N \phi_{ij}^2} \text{ assuming identical mass at each story} \tag{3.3}$$

Φ, *ξ* and *ω* are the *N* modal parameters of the building (mode shapes, damping ratios and frequencies) and *p* is the modal participation factor.

The considered damage parameter is the inter-story drift, easily computed from the displacement at each story, that is compared to threshold values for the slight damage state extracted from the literature. This value is $4\text{x}10^{-3}$ for RC shear walls, $3\text{x}10^{-3}$ for RC infilled frames and 10^{-3} for masonry structures (FEMA, 2003). These values should be refined based on laboratory tests in the future. If this threshold is exceeded, the building is considered as at least slightly damaged, without more precision since the model is no more valid above this threshold.

In order to study the vulnerability of a building class, median values of the resonance frequencies, damping and modal shapes are computed to build a “median model” for each class. In the future, the classes can be easily split into number of stories classes. The number of stories is indeed a parameter easy to retrieve and critical from the point of view of the earthquake response. This information for each type of buildings for the whole city was not available at the time of the study. These models are used to estimate the slight damage fragility curve as explained below.

3.2. Fragility curves: variability and uncertainty

Fragility curves are representing the probability of reaching a given damage grade for a given ground motion level. Most of the researchers agree on a lognormal model to represent fragility curves, therefore limiting their description to 2 parameters: a median value and a lognormal standard deviation. The most critical question is to determine what sources of uncertainties should appear in fragility curves. It is now well known that uncertainties should be separated in aleatory and epistemic uncertainties. However, it is less obvious that assigning the adjective aleatory or epistemic to uncertainties is problem-dependent (Bradley, 2010). Depending on the problem, the same uncertainty may be considered as epistemic or aleatory.

In case of a study at the city-scale, the fragility curve represents the distribution of damage that should be observed in case of earthquake. It should therefore include only the aleatory uncertainties namely: 1) the aleatory uncertainty on the ground motion parameter and 2) the aleatory uncertainties due to the grouping of buildings to a single class (modelling parameters only). The epistemic uncertainties due to the simplification for the generic model (geometry, behaviour law and quality of the chosen damage

parameter) should not be included in the fragility standard deviation since they are not part of the observed variability in damage after an earthquake. They should however be captured to estimate the uncertainty on the fragility median. As a consequence, epistemic uncertainties cannot be validated. In practice, the estimation of epistemic is not performed at the moment, nor in the present study but this is a very important point for future studies.
The largest source of aleatory uncertainty is the grouping into building classes (Spence et al., 2003): two single buildings of the same class may for sure have different behaviour. One could argue that it can be decreased by increasing the number of classes, but this would change the initial problem, limited by the resources for the study.

Fragility curves are functions of a ground motion parameter, sometimes called Engineering Demand Parameter (EDP). The choice of this parameter depends on the possible input for the model used, on the available ground motion parameters for a future scenario or observed data etc. Common EDPs are the macroseismic intensity, the peak ground acceleration or the spectral acceleration/displacement at a particular frequency. The better representing the actual threat on the building, the lower the uncertainty in the fragility curve. Therefore, in our case, we used the elastic spectral displacement at the fundamental frequency and damping of the considered model. The increase in the standard deviation when using PGA instead is very large (Michel et al., 2012).

In order to derive fragility curves the model described in the previous paragraph, the median model loaded using a database of ground motion time histories. This database is a subset of 164 signals from the European strong motion database described in Lestuzzi et al. (2007). For a building class, characterized by a model based on experimental modal parameters, the probability of exceeding damage grade "slight" for each bin of spectral acceleration is computed. A lognormal curve function of the spectral displacement is then fitted.
This procedure allows to estimate the variability due to the quality of the ground motion parameter. The variability due to the grouping into building classes affects the different parameters of the model: frequencies, modal shapes, damping ratios as well as inter-story drift threshold for slight damage. This last parameter is probably the most variable into a single class since it depends on the geometry of the structure, the quality of execution etc. However, no value is provided in the literature for this variability and the standard deviation related to it was supposed to be 0.35, corresponding to 95% probability to have the value in between the half and the double of the median value. This standard deviation is added to the previously found standard deviation using the L2 norm (square root of the sum of the squares). The resulting curves are presented on Fig. 2.

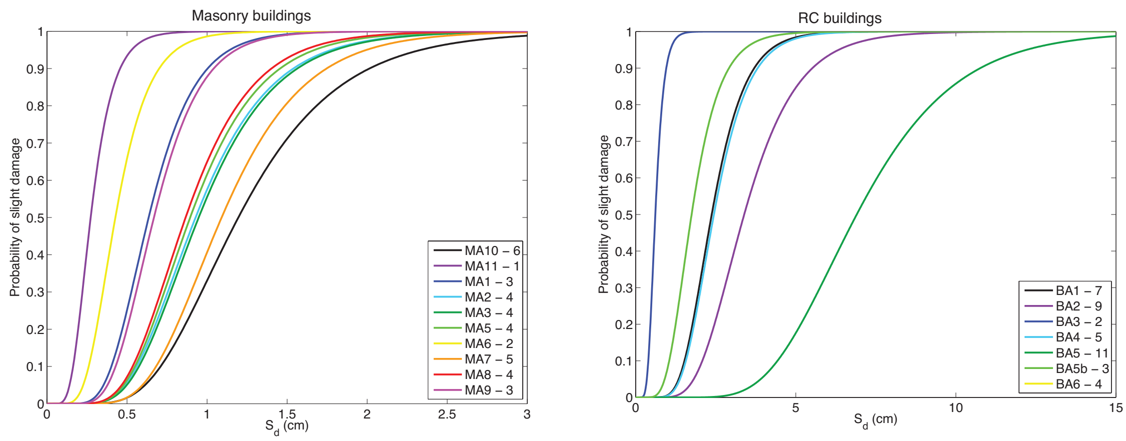

Figure 2. Fragility curves for slight damage for the different building classes in Grenoble

4. SCENARIO FOR GRENOBLE

In this work, the city of Grenoble was divided into zones of assumed homogeneous building distribution. The distribution of the classes in each zone of the city was assessed by sample screening. The ground motion was calculated only at one position of the city. This exercise aims at focusing on the effect of the vulnerability on the damage distribution. However, for a more realistic scenario, single buildings should be considered with their class, height and position in the city and ground motion variability across the city should be accounted for.

As explained above, seismologists now provide ground motions with realistic frequency content, accounting for source and site effects. Many studies on the effects of the Grenoble basin on the ground motion can be found in the literature (e.g. Guéguen et al., 2007). For this application, we used a ground motion computed using Empirical Green's function method (Causse et al., 2008). It simulates a magnitude 5.5 earthquake located 15 km away from the city centre, based on a recording of a magnitude 2.3 earthquake at the same location and recorded at station OGDH of the French Accelerometric Network (http://www-rap.obs.ujf-grenoble.fr/), located in the city centre. The method reproduces the effects of local geology on the ground motion.

Results of the distribution of at least slight damage using the proposed methodology are displayed on Fig. 3. The distribution of damage is more complex than expected: there is a clear gradient of vulnerability in the sense of EMS98 from the old city centre made of stone masonry structures to the suburbs made of RC structure. However, the damage does not reflect this gradient due to the amplification in a given frequency band in the ground motion that tends to load more high-rise RC structures than masonry buildings. This result shows clearly that empirical methods cannot capture the damage distribution since they cannot account for this effect. One should therefore tend to physics-based assessments and insist on providing realistic dynamic parameters for structures. This will obviously not allow to capture all the complexity of the damage distribution but it is feasible and decreases drastically the uncertainties.

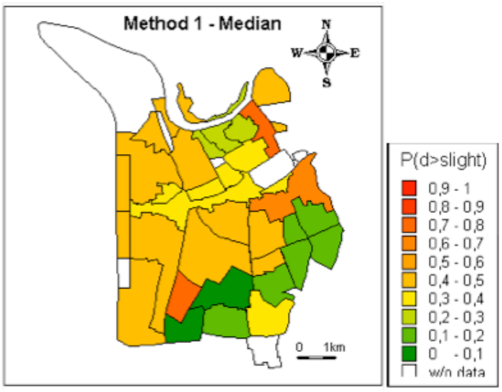

Figure 3. Damage distribution in the city of Grenoble: rate of structures exceeding the slight damage state in each zone.

5. CONCLUSIONS

The main goal of this work was to show that experimental dynamic parameters extracted from ambient vibrations can enhance critically earthquake loss assessment. Each building is modelled as a whole based on dynamic parameter obtained from in situ data and its response is therefore better modelled, at least at low strain, though the model remains simple. Damage is based on the inter-story drift and is therefore compatible with most of the existing vulnerability methods. Moreover, the model including the used ground motion, follows the 'principle of consistent crudeness': no particularly crude information is dominating the uncertainty on the results, and conversely, no part of the process is particularly detailed without justification.

The weakest part of the method is obviously the fact that the model is elastic and therefore limited to slight damage. First of all, the information if an event was damaging or not is very important for the authorities in terms of rapid response but also insurance coverage. Moreover, the model used is a good linear starting point and is flexible enough to allow a coupling with mechanical models accounting for non-linearities in the structure. Michel et al. (2011a) proposed a relationship describing the frequency drop in masonry buildings as a function of displacement amplitude. This relationship was included in the model proposed here and will allow to describe realistically the behaviour of the structures at higher strains. Another issue is the effect of soil-structure interaction (SSI) that may be critical in some cases in the resonance frequencies of buildings and their evolution in time, and therefore to refine the vulnerability assessment. In Michel et al. (2011b) we investigated a new technique to observe the effects of SSI on resonance frequencies.

This work showed the importance of physics-based simulation for earthquake loss assessment and the importance to base it on observed data.

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