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On the Contribution of Experimental Data to the Reduction of the Uncertainty of Fragility Curves

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Abstract

Ambient vibrations in buildings is of increasing interest for applications in mechanical engineering, civil engineering and earthquake engineering. For example, elastic fundamental frequency and damping ratio are two key-parameters for simplified seismic design and vulnerability assessment methods. Empirical relationships exist in codes to estimate this frequency and damping but experimental data could be used to improve them, accounting for national features of building design and, above all, the corresponding uncertainties. With advances in data acquisition systems (the number of measurement points, continuous recording, low-noise instruments) and advances in signal processing algorithms, further and better studies can be conducted on civil engineering structures for evaluating their modal parameters and their physical properties, with a high level of confidence. Moreover, permanent instrumentations also provide earthquake data helping in the improvement of the building response in case of a severe event. The aim of this paper is to show how the experimental data, providing from temporary or permanent instrumentation, can be used for adjusting behaviour models for each class of structure for vulnerability assessment, for monitoring the wandering effect of the elastic parameters on the fragility curves and their uncertainties.

Keywords: ambient vibration, modal parameters, seismic vulnerability.

1 Introduction

Building response assessment under moderate-to-strong shaking is a multi-disciplinary activity, including structural engineering, signal processing and earthquake engineering applications. Most of these activities result in searching physical parameters that provide information on the building characteristics, and therefore its seismic behavior and resistance in case of earthquakes. Since the design forces in structures are frequency and damping dependent (based on the seismic coefficient $C(T, \xi)$ where T is the period of the building and ξ is the damping ratio), these two parameters are the subject of special attention and focus of many research activities. For example, these parameters can be used for fixing numerical and enhanced models (e.g., [1], [2], [3]), for providing empirical relationships between the main characteristics (height, design...) of buildings and their period of vibration (e.g., [4], [5], [6]) and finally found in the seismic regulation. In parallel to the seismic response assessment, additional activities are promoted by the fact that new instrumentations and new signal processing exists. Design and construction of more and more complex and ambitious structures need tools for exploring their response.

Over the last two decades, efforts have been made in moderate seismic regions to update Eurocode 8 [7], by improving the seismic hazard evaluation using probabilistic seismic hazard assessment (PSHA) methods, and by including recent knowledge on structural dynamics theory. Nevertheless, most losses produced by earthquakes throughout the world are due to deficient seismic behavior in existing buildings in spite of improvements made to seismic codes [8]. A critical step in seismic risk assessment is therefore to be able to predict the expected damage for a given earthquake in existing structures. In the literature (see [9] for a complete review), the first vulnerability methods were developed in strong seismic regions, based on post-seismic inventories used to adjust continuous (Vulnerability Functions VF) or discrete (Damage Probability Matrices DPM) functions of seismic damage. DPM give the conditional probability of obtaining a specific damage level for a given level of hazard severity while VF provide average damage for a given level of ground motion. Since the publication of these methods, they have been widely applied in-extenso especially in regions without recent destructive earthquakes that allowed to calibrate the vulnerability curves including the regional specific design. In this way, the vulnerability analysis can be biased and introducing some epistemic uncertainties. Spence et al. [10] supported that the adjustment of structural models should assume a large set of unknown parameters influencing the response of existing buildings and introducing a large range of errors and epistemic uncertainties for the establishment of fragility curves, generally due to the lack of structural plans, aging and structural design.

One solution to reduce these epistemic uncertainties is to perform field testing in buildings, providing an estimate of the elastic modal parameters of structures (resonance frequencies, damping ratios and modal shapes). Weak and strong excitations can be used, their characteristics and recording devices deployed in the structure having influences on the data processing (output only or input-output methods), the interpretation (linear or non-linear behavior), and their applicability (building specific analysis or by typologies).

The main goal of this paper is to show how field testings can be implemented into vulnerability assessment, by contributing to the improvement of the building knowledge for earthquake engineering applications, by developing a seismic vulnerability strategy based on experimental testing and then by reducing the uncertainties of the fragility curves. After a brief remain of the first application for earthquake engineering, the stability and accuracy of the experimental modal parameters are discussed.

2 Experimental assessment of building characteristics for earthquake engineering

The first and extended program for earthquake survey in building started in 60s in USA. The main objective was focused on the understanding of the building seismic response by processing and interpreting the data collected in the structure. A large number of applications were then conducted on some basic observations that were at the origin of crucial and important understandings: the effect of the soil conditions on the seismic response (e.g. [11], [12], [13], [14]), the mode of deformation of the buildings (e.g., [15], [16]), the nonlinear response of the structures with increasing shaking (e.g., [17], [22]). In fact, using the strong motion data collected in buildings, authors showed that transient frequency variations could appear during earthquakes due to the opening and closing process of pre-existing cracks in the structure (Figure 1). During earthquakes, a permanent loss of structural stiffness is observed and thus a permanent decrease of the fundamental frequency. In Japan, Satake [18] has also compared the decrease of the frequencies during earthquakes in steel buildings. In Mexico, Meli et al. [19] instrumented a 14-storey building and studied the importance of soil-structure interaction under earthquake and the decrease of the frequency with amplitude of shaking. For example, transient variations are observed during seismic excitation due to the non-linear response of the soil-structure interaction [20] [21] or to the closing/opening process of the pre-existing cracks located inside reinforced concrete elements of the building [22] [3]. Permanent variations may also appear due to structural damage in case of strong seismic motion (e.g., [23] [22]). For this reason, monitoring the frequency of buildings may be useful to detect the damage after earthquakes, as recently shown in practice by Dunand et al. [24] after the Boumerdes, Algeria (May 21, 2003) earthquake. Laboratory dynamic or pseudo-dynamic tests also showed such a frequency decrease with increasing damage [25].

In the middle of 80's, numerical modeling gained more and more interest and the activities related to field testing decreased. Nevertheless, while the first application were focused on the understanding of the data, some recent applications have emerged again, taking advantages on recent developments of signal processing theory and more than anything by the accessibility of the new extensive data and the performance of modern system. For example, wave propagation analysis in buildings was proposed for computing the shear deformation of the building, characterizing then the dynamic parameters of the building [26], [27], [28], encouraged also by the new instruments used for monitoring buildings.

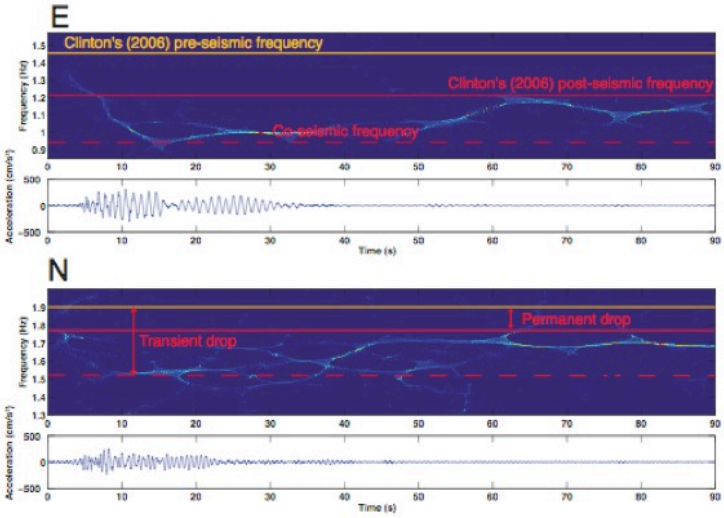

Figure 1: Time-Frequency distribution (smoothed reassigned pseudo-Wigner-Ville) of 1971/02/09 ML=6.6 San Fernando Earthquake recordings at the roof of the Millikan Library on CalTech campus (California) in E (top) and N (bottom) directions.

Clinton et al. [29] demonstrated the evolution of the accelerometric sensors coupled to modern 24-bit digitizers, increasing the resolution and the range of amplitude of signal and having also an absolute time reference for each recording. One can also note the instrumentation of structures in moderate-to-weak seismic prone regions, as for example in Romania [30] or in France with 5 buildings of the Building Array National Program of the French Accelerometric Networks (RAP, [31]). Actually, the UCLA Factor Building is certainly the best instrumented building in the world with 72 components continuously recording the vibrations [32], [33].

In all cases, experimental analysis of the seismic response of existing buildings is certainly the only way for having the real behavior of the structures. Usually, input-output methods are used [34], [35] which boil down to analyze simultaneously the input (usually at the base of the building) and output (top of the building, for example) signals to identify the properties of the structure. No assumptions on the design, the system of foundation or the quality of the material are required for processing the data and their interpretations are a crucial step in the understanding of the dynamics of structure. Moreover, as for all observatory systems and activities devoted to monitor natural earth phenomena, long-term observations and data acquisition are needed to acquire sufficient data and experiences of earthquakes, the only way for leading to the formulation of relevant conclusions and the development of new theories and new hypothesis for improving the seismic response of structures.

An other source of shaking exists in building: the ambient vibrations (AV). Am-

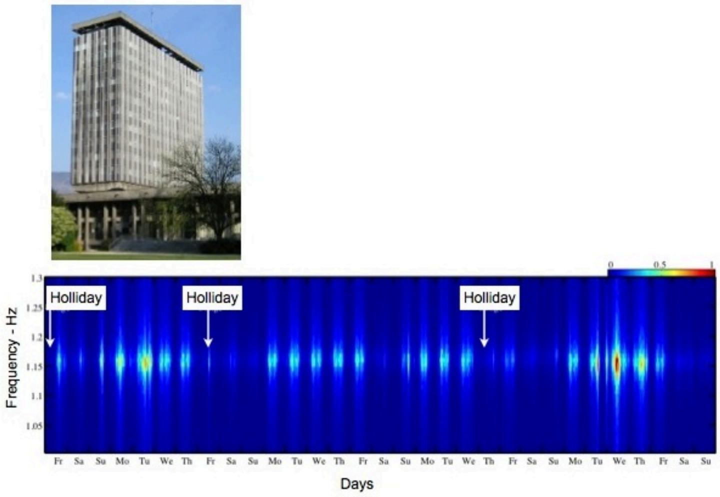

Figure 2: Fourier transform of the ambient vibrations recording at the top of the City-Hall building of Grenoble during May 2009 (after [37]).

bient vibrations are produced by the wind (low frequencies $< 1Hz$), internal sources (machinery, lift at high frequencies) and seismic noise (broadband) (Figure 2). Since the design forces in structures are based on the seismic coefficient $C(T, \xi)$, the use of AV methods provides relevant information on the elastic characteristics of the building at reducing cost. Widely used throughout the engineering and aerospace communities, ambient vibrations based methods have been first developed for detecting and locating damages, mainly by comparing initial and final values of frequencies, damping and mode shapes. Farrar et al. [36] mentioned that frequencies are certainly the most sensitive modal parameters to changing, especially because the loss of stiffness directly impacts the frequency values.

3 Using ambient vibrations for structural analysis and damage assessment

3.1 Frequency analysis

Omori [38] was the first to use ambient vibration to earthquake engineering in the early 20th century in Japan to evaluate how existing buildings would move to resist against earthquakes. Carder [39] was also a precursor, recording ambient vibrations in 336 buildings in California for the U.S. Coast and Geodetic survey after the 1933 Long Beach earthquake. Trifunac [40] in US confirmed the interest of ambient vibrations, considering the low cost of recording and the reliability of the associated results compared to active experiments (e.g., shaker, pull-out-test, explosion, etc.). Since then,

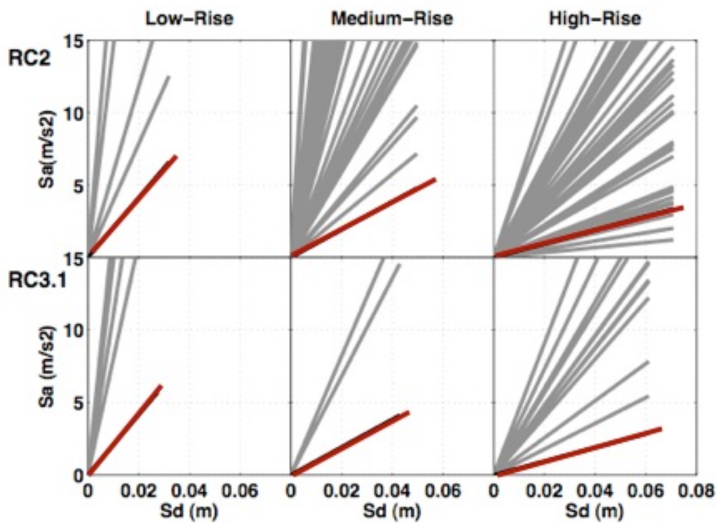

Figure 3: Elastic part of the experimental capacity curves obtained from all the structures in [6] (grey) compared to Risk-UE curves [44] (black) for different classes of RC-buildings (after [6]).

and in parallel to the development of sensitive and portable acquisition systems, many experiments on the relevance of ambient vibrations in structure were conducted in the nineties by the civil engineering community. Recent papers ([4], [5], [6]) provided other relationships for European buildings having different design. These relationships can be introduced into vulnerability assessments, to fit the building capacity curve, at least the first part whose slope is proportional to the elastic frequency [42]. Nevertheless, this frequency is usually supposed to be overestimated by the design codes in order to be conservative in conventional design [43] but the requirements for seismic assessment may be different. Michel et al. [6] have shown very large uncertainties on these curves by the experimental data used for a large number of buildings (Figure 3). A large part of this uncertainty may be removed by fixing it with experimental assessment of the frequency. Moreover, empirical curves can not be always adapted for the typical buildings found in one region and region-specific curves must be proposed to take local design practice into account.

3.2 Modal analysis

Using ambient vibrations comes down to consider only the output signal (i.e., output only methods) as known and extract informations on the structure. Nevertheless, two approaches can be selected for processing data, depending on the fact that an a priori model is known (parametric method) or not (unparametric method). For example, Figure 4) displays the decrease of the Fourier spectra amplitude along a tall building, corresponding to the shape of the first three modes, assuming an a priori continuous

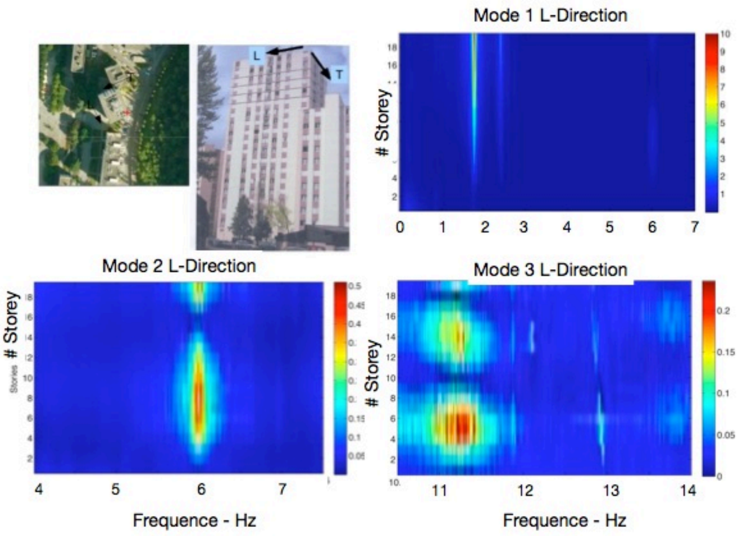

Figure 4: Peak-picking analysis along the Ophite Tower (France). The decrease of the Fourier spectra amplitude along the beam at three different frequencies shows clearly the shape of the three modes, with the nodes of the modes at different heights.

beam model. Sometimes, the Fourier spectra of ambient vibrations at the top of the building does not allow us to fit a parametric model at the time of the signal processing (Figure 5). For that reasons, non-parametric methods must be employed, the extraction of the buildings characteristics being usually given as function of the mode shapes, modal frequencies and damping. By comparing experimental analysis and 3D numerical modeling applied to the City-Hall of Grenoble, Michel et al. [3] have shown the relevancy of the experimental approach for fixing the elastic properties and boundaries conditions of the model. This method can be used to fill in some information missing for existing buildings. In addition, once the model is made and fixed, it is possible to evaluate the seismic response of the structure to a stronger earthquake mobilizing the laws of sophisticated non-linear behavior (e.g., [1], [2]).

Since the response of structures is related to its modal model, experimental mode shapes can be used also for defining the right model of the building including all in-situ characteristics of the structure. This method is less time consuming than numerical modeling, which allows to consider its application on a large scale for a large number of buildings and to distinguish the type of construction according to their modal characteristics. For example, Michel et al. [45] explored an ambient vibrations based method for producing fragility curves corresponding to slight damage, that is to say at the end of the validity domain of the ambient vibration model. A fragility curve expresses the conditional probability $P[D = j|i]$ that a building exceeds a given damage state j for a given level of shaking i. A lognormal distribution function is fitted to the results of the model, this distribution is defined by the median of the seismic demand

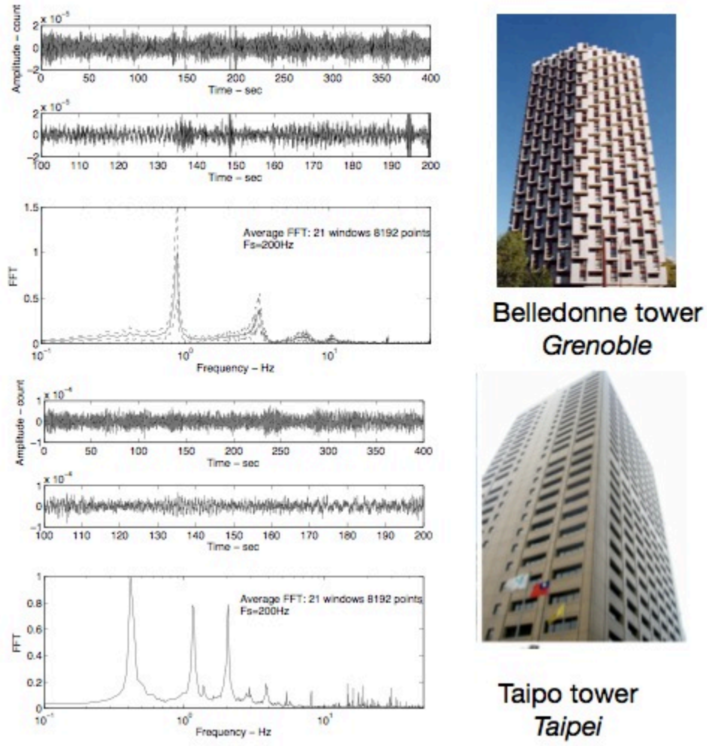

Figure 5: Example of Fourier transform of ambient vibrations recorded at the top of two towers: Belledonne tower in Grenoble, showing a typical response of building, with the three first damped modes (upper row) and the Taipo tower in Taipei, for which the response is not clearly visible without further analysis (lower row).

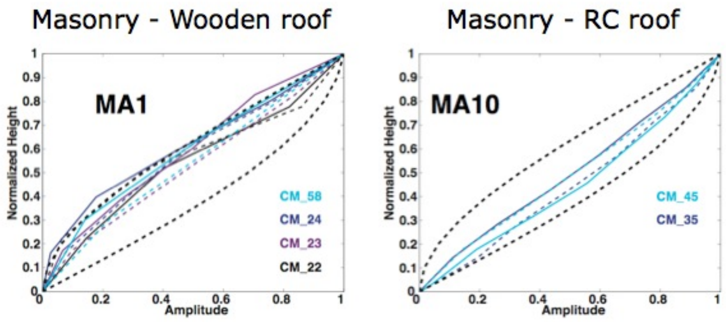

Figure 6: Modal analysis using ambient vibrations applied to a set of two different types of buildings: MA10 masonry with RC roof having a behavior close to the theoretical bending beam model (dotted black line) - MA1 masonry with wooden roof having a behavior close to theoretical shear beam model (dotted black line)

parameter and the corresponding lognormal standard deviation σ. The entire variability of the fragility curve σ includes the variability due to epistemic uncertainties σ_C , the uncertainty on damage parameter considered (e.g., the inter-story drift parameter) σ_{ds}, and the variability of the shaking intensity σ_D, in giving a damage grade. If the variabilities are considered to be independent, total σ is given by the sum of all sigma ($\sigma^2 = \sigma_C^2 + \sigma_{ds}^2 + \sigma_D^2$).

The epistemic uncertainty σ_C is associated with the classification of the buildings into a vulnerability class and the assignment of a generic behavior type (analytical model) to each class of building [10]. By using models based on experimental values and taking higher modes into account, epistemic uncertainties are reduced, especially for high-rise buildings where the higher modes play a key role in the response. By this approach, Michel et al. [45] carried out to raise ambiguities successfully about the model of the building, and thus improve the estimation of vulnerability (Figure 6).

4 Measurement accuracy

AV modal analysis based methods provide also an effective tool for short- and/or long-term health monitoring of buildings, such as those due to aging effect or after extreme event, mainly by comparing initial and final values of frequencies, damping and mode shapes [24]. These variations may be very slight, such as recently and in-situ observed by Clinton et al. [22] and Todorovska and Al Rjoub [20]. In that case, they showed that long term and slight variations of fundamental frequency of buildings could be related to the temporal variations of the atmospheric conditions (temperature, humidity...) influencing the building and soil properties. Most of the previous studies conducted in civil engineering structures (e.g., [22], [46], [47], [48], [49]) have shown the temperature is the most significant cause of variability of modal frequencies. Most of scientific papers dealing with experimental and in-situ data are focused on the fundamental frequency tracking. Nevertheless, the variation of the parameters of each mode will not be affected in the same manner, depending on the position, the amplitude and the nature of the perturbation [50]. For instance, laboratory and numerical analysis showed the efficiency of frequency analysis for damage detection considering fundamental mode and overtones (e.g., [51]; [52]). Moreover, a major difficulty to overcome is that the damage can be very localized and it may not significantly influence the overall response of a structure evaluated only with the fundamental frequency. Since recorded at one point, variation of frequencies may only reflect a global change of the system properties and it is not often sufficient to locate inside the structure the origin of changing. For that reason, damage detection methods have been developed based on the mode shapes analysis, such as the mode flexibility method [53], the curvature flexibility method [54], the mode shape curvature method [55] or a combination of these methods. Nevertheless, the experimental assessment of mode shapes are less precise and such as methods are not able to detect and locate small variations, compared to the sensitivity of the modal frequencies analysis.

Mikael et al. [49] have shown small variations of frequency and damping, not related to the integrity of the building, assuming that less than 0.5% variation of the building fundamental frequency cannot be related to structural health but only to the natural fluctuations. This information is thus relevant for building monitoring, especially after extreme events when building tests using ambient vibrations are performed and compared with pre-event characteristics. Since the measurements are reproducible and stable with no variation other than natural, the modal parameters estimation using ambient vibration methods may be useful for reducing the models uncertainties which are included in the fragility curves for seismic vulnerability [45]. Mikael et al. [49] also showed σ was less than 0.01Hz and 0.2% for the frequency and damping values respectively (Figure 7 8), while Nayeri et al. [48] obtained order of magnitude of the coefficient of variation σ/μ computed for the first mode close to 1% with $\sigma = 0.005Hz$ for frequency, and close to 60% for damping with $\sigma = 2.0\%$.

Concerning the mode shapes assessment, one building tested in Grenoble (ARPEJ building, [45]) shows stable mode shapes and frequencies after 10 years of measurements, with Modal Analysis Criteria (MAC) value close to, that is to say less than 0.1% and 2% of variations for the first and third modes, respectively, whatever the year and the operator (Figure 8).

5 Conclusion

The scientific interests of large-scale instrumentation and monitoring of existing buildings are then the monitoring of the structure in time, the assessment in changing the physical properties of structures between before and after earthquake for seismic dam-

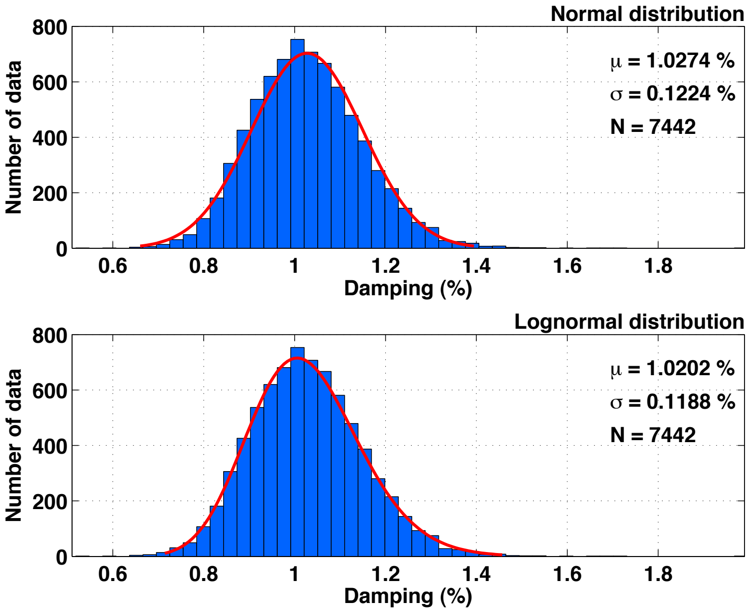

Figure 7: Normal distribution and log normal distribution (red line) adjusted to the damping values obtained at the City-Hall building in the transverse direction. Ambient vibrations are processed using the Random Decrement Technique (after [49]).

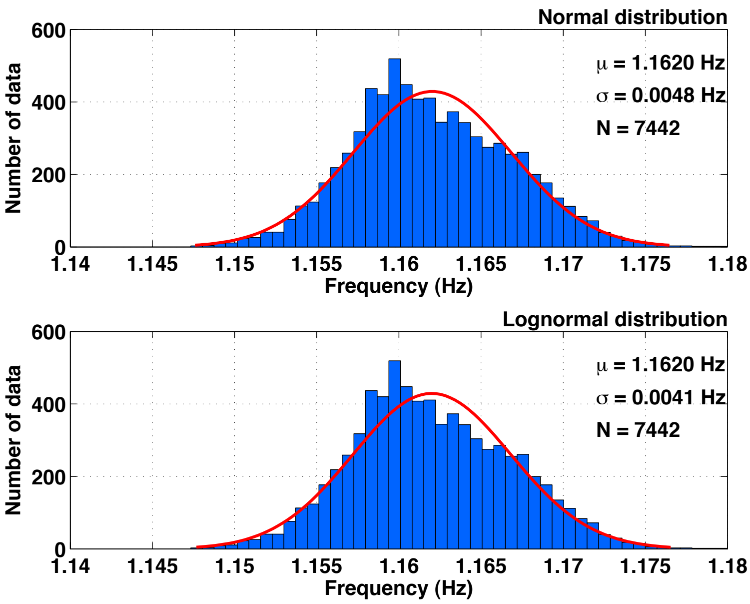

Figure 8: Normal distribution and log normal distribution (red line) adjusted to the frequency values obtained at the City-Hall building in the transverse direction. Ambient vibrations are processed using the Random Decrement Technique (after [49]).

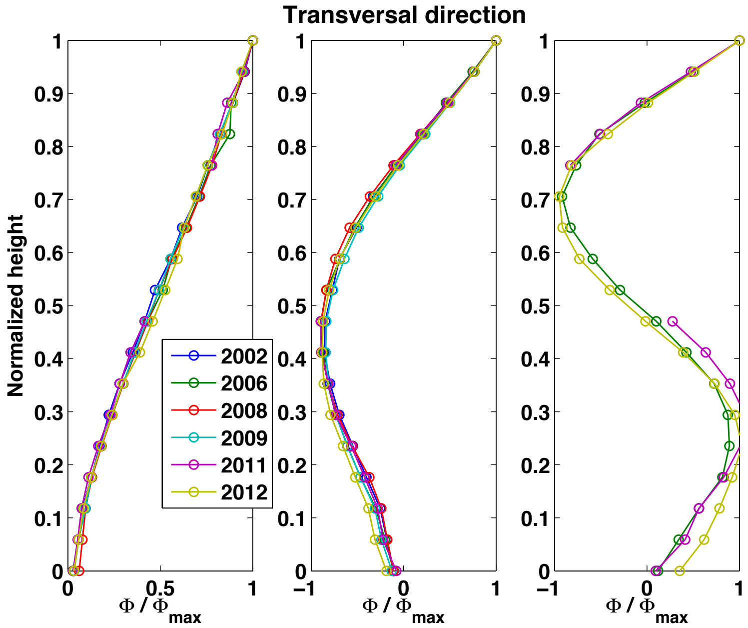

Figure 9: Stability of the experimental mode shapes extracted from ambient vibrations recordings using the Frequency Domain Decomposition for 10 years of testings.

age assessment and the understanding of the building response to external shaking. Improving the knowledge of the building characteristics reduces the uncertainties of the fragility curves. Ambient vibrations help to improve seismic vulnerability assessment by reducing the epistemic uncertainties due to the lack of knowledge in building models. Ambient vibration-based methods help to adjust the building model to realities in the field. The modal model derived therefore allows some design specificities to be taken into account and is adapted to the recent definition of seismic hazard: full waveform or response spectra may be employed to estimate whether or not the building may suffer from damage by the end of shaking.

The quality and relevancy of the modal parameters extracted by this approach are good. Moreover, recent initiatives started, taking advantages of the reducing cost of news instruments (such as MEMS sensor, Micro-Electro- Mechanical Systems) for improving the building monitoring. The Quake Catcher Network (QCN) employs existing laptops to form a dense and distributed computing seismic network installed in buildings, schools etc... [56]. The QCN capitalizes on the main advantage of distributed computing - achieving large numbers of processors with low infrastructure costs - to provide a dense, large-scale seismic network. While MEMS accelerometers are less sensitive than typical broadband or short-period sensors, a larger number of stations is advantageous for both the study of earthquakes, structural health monitoring and, potentially, earthquake crisis managing.

The ability of Lidar to measure the modal frequencies of existing buildings has been shown in [57]. By comparing the vibration spectra obtained by sensitive velocimeter sensor and coherent Lidar sensor, they observed a good fit of the values of modal frequencies detected by both approaches. Even if the level of noise is higher for Laser remote sensing (10^{-6}m/s) than velocimeter (10^{-7}m/s), most of the existing buildings could be checked by this method for whole urban area covering.

Acknowledgement

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