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FULL SCALE DYNAMIC BEHAVIOUR OF A RC-BUILDING UNDER LOW-TO-MODERATE SEISMIC MOTIONS

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ABSTRACT

In countries with a moderate seismic hazard, the classical method developed for countries with strong earthquakes to estimate the behaviour and subsequent vulnerability of buildings during earthquakes are often inadequate and not financially realistic. An alternative method is proposed whereby the structural characteristics of the building are obtained by using experimental values of the modal parameters. This article describes the application of a sophisticated modal analysis technique (Frequency Domain Decomposition) to process ambient vibration recordings taken at the Grenoble City Hall building (France). The frequencies of ambient vibrations are compared with those of low-to-moderate earthquakes recorded by the permanent accelerometric network that was installed to monitor the building. The frequency variations of the building under moderate earthquakes are shown to be slight and therefore ambient vibration frequencies are relevant over the entire elastic domain of the building. The modal parameters extracted from ambient vibrations are then used to determine the lumped-mass model in order to reproduce the building motion under moderate earthquakes.

Introduction

Since the 30s, earthquake engineers have recorded and studied the ambient vibrations of buildings (Carder, 1936). They were especially interested in the resonance frequencies for design code and engineering purposes (e.g. Housner and Brady, 1963). In the 60s and 70s, new forcing methods (explosion, harmonic forcing, etc.) were proposed to reach higher amplitudes of motion. Nevertheless, Crawford and Ward (1964) and Trifunac (1972) showed that ambient vibration-based techniques were as accurate as active methods for determining vibration modes and much easier to implement for a large set of buildings. Simultaneously, in the last 20 years, modal analysis techniques in civil engineering applications have been considerably improved thanks to

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technical (instrumentation, computers) and theoretical developments in modal analysis in the electrical and mechanical engineering fields (Peeters and De Roeck, 2001). These new techniques may be extremely useful for understand the dynamic behaviour of buildings and fixing their elastic properties by means of their modal parameters (frequency, damping and modal shape). These are the main parameters controlling building response and vulnerability. The major difficulty in the seismic vulnerability assessment of existing buildings is the lack of available data such as quality of material, structural plans, ageing and damage. In such cases, the classical tools in earthquake engineering may turn out to be very expensive or lead to over-simplistic hypotheses to overcome these difficulties.

This paper studies the response of Grenoble City Hall (France), a 13-storey reinforced concrete building, using ambient vibration tests and the network of permanent accelerometric monitoring stations installed by the French Permanent Accelerometric Network. The results of the modal analysis of the building using low-to-moderate earthquakes recorded in the structure are compared with those of the ambient vibration survey. The accelerometric data observed at the top of the building are then compared to those predicted using a lumped-mass model adjusted using the modal analysis results obtained from ambient vibration recordings and to an enhanced 3D numerical model.

The Grenoble RC City Hall building

The city of Grenoble is located in the northern French Alps (Fig. 1), one of the most seismic-prone areas in France (a_N=1.5 m/s^2 for the national seismic code PS92). Several strong historical events have occurred in the surrounding area and the regional seismic network indicates an active fault along the Belledonne range, 15 km from the city (Thouvenot et al., 2003). Furthermore, the city is founded on a very deep sedimentary basin which and this gives rise to strong site effects (Guéguen et al., 2007). The Grenoble City Hall is a stand alone RC structure completed in 1967 (Fig. 1). It is divided into two parts: a 3-level horizontal building and an independent 13-story tower that is the subject of this study. The tower has a 44 m by 13 m plan section and rises 52 m above the ground. The inter-storey height is regular between the 3rd and 12th floors (3.2 m) and higher for the 1st (4.68 m) and 2nd storey (8 m), above which there is a precast slab of 23 m span supported by two inner cores. These cores, consisting of RC shear walls, enclose the stair wells and lift shafts and are located at two opposite sides of the building. The structural strength system combines these shear walls with RC frames with longitudinal beams bearing the full RC floors. The foundation system consists of deep piles, anchored in an underlying stiff layer of sand and gravel. Since November 2004, the building has been monitored by six accelerometric stations (Fig. 2), three on the ground floor called OGH1, OGH2 and OGH3 and three on the 13th floor called OGH4, OGH5 and OGH6 (Michel et al., 2009). This instrumentation is part of the French Permanent Accelerometric Network (RAP, Péquegnat et al., 2008), which is in charge of recording, collecting and disseminating accelerometric data in France. The City Hall network is managed by the Geophysical Laboratory of Grenoble University (LGIT). Each station consists of one 3C Episensor (Kinemetrics) accelerometer connected to a 24-bit digital acquisition system.

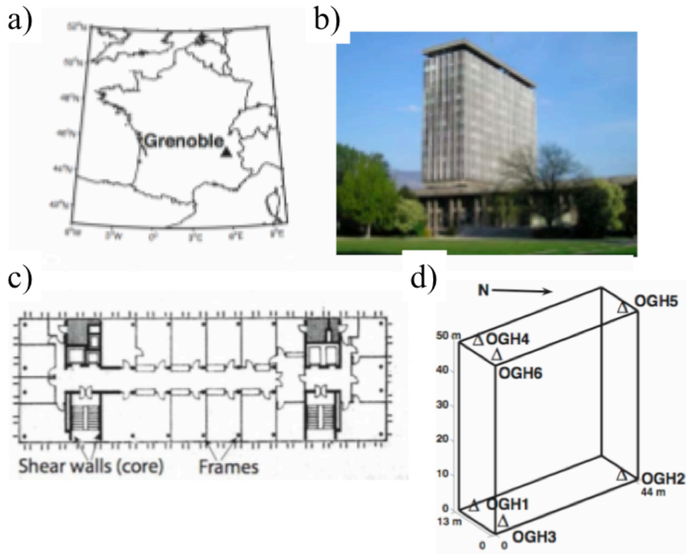


Figure 1. a) Location of the Grenoble City-Hall in France. b) Overview of the building. c) Structural plan of the building (current floor). d) Location of the 6 permanent 3C accelerometric stations in the building.

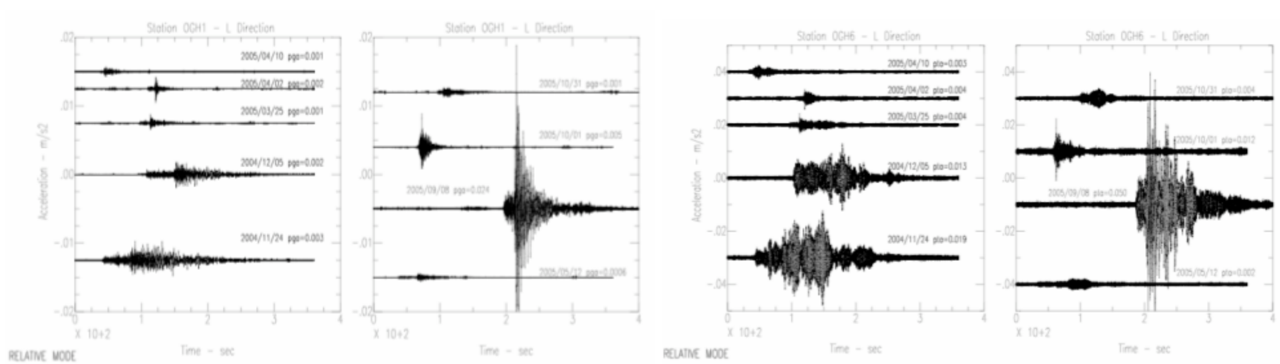


Figure 2. Examples of accelerometric time history of the nine earthquakes in the Grenoble City Hall recorded at the OGH6 roof station (right) and at the OGH1 ground station (left) in the longitudinal L directions. All the waveforms are plotted in relative mode and scaled by the maximal amplitude of each station/component pair.

The horizontal components are oriented along the longitudinal and transverse directions of the building, with the longitudinal direction having an azimuth of 327°N. The sampling rate is 125 Hz and the recordings are divided into files of 2 minutes in length. Time is controlled by a GPS receiver located on top of the building. The stations are connected via an Ethernet hub allowing data transfer from each station to the computer located in the basement of the building. This computer is permanently online for remote data control and station management. The dial-up data retrieval system at the LGIT extracts the data from the continuous recordings in accordance with a list of epicentres provided by the national seismological survey (RéNaSS).

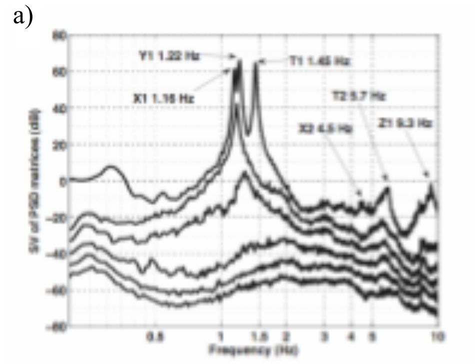
Within the context of this study, a temporary network was also installed to determine the full-scale behaviour of the structure under ambient vibration. A Cityshark II station (Chatelain et al., 2000) was used for the simultaneous recording of 18 channels. Six Lennartz 3D 5s velocimeters were used for this purpose, having a flat response between 0.2 and 50 Hz. Eight datasets were recorded, corresponding to 36 different points in the building, i.e., at least two points per floor. One sensor was installed on top of the building to serve as reference instrument for all the datasets . This reference point is necessary in order to normalize and combine all the components of the modal shape. The first frequency was estimated to be close to 1 Hz, so a 15 min recording time was selected for each set, corresponding to more than 1000 periods, at a 200 Hz sampling rate.

Ambient vibrations recordings performed in the building

In order to extract the modal parameters of the structure from ambient vibration, we used the Frequency Domain Decomposition (FDD) method (Brincker et al., 2001a). This method is able to decompose modes, even if they are very close that may be the case for current buildings. The first step of this method is to calculate the Power Spectral Density (PSD) matrices for each dataset (Michel et al., 2008). For this purpose, we used the Welch method, i.e. the modified smoothed periodogram for which Fourier Transforms of the correlation matrices on overlapping Hamming windows are averaged over the recordings. As we record 18 channels simultaneously, the sizes of these matrices are 18x18 for each frequency. Only a limited number of modes (frequencies λ_k, mode shape vectors $\{\phi_k\}$) has energy at one particular angular frequency ω. This method is able to decompose these modes on the contrary to the traditional "Peak Picking" method. Moreover, this method can be enhanced (Brincker et al., 2001b) to select the complete mode "bell", and consequently its damping ratio, by comparing the mode shape at the peak to the mode shapes of the surrounding frequency values. This can be done using the Modal Assurance Criterion (MAC) (Allemang and Brown, 1982) that compares two modal shapes Φ_1 and Φ_2. For a MAC value greater than 80%, we consider that the point still belongs to the mode "bell", even on the second singular value. The bell then represents the Fourier Transform of the auto-correlation of the mode so that an inverse Fourier Transform leads to the Impulse Response Function (IRF) of the mode. The logarithmic decrement of the IRF gives the damping ratio and a linear regression of the zero-crossing times gives the enhanced frequency. Considering the extent of the mode "bell", the damping ratio and the shape, one can decide whether a peak is a structural mode or not.

Only 3 modes have been accurately determined (Fig. 3): the first longitudinal mode at 1.157±0.006 Hz, with a damping of about 0.9%, the first transverse mode at 1.217±0.006 Hz with a damping of about 1.1% and the first torsion mode at 1.45±0.01 Hz with a damping of about 0.9%. The first longitudinal mode is not pure but has a slight torsion component on the contrary to the first transverse mode. Following the aforementioned decision process using MAC, the longitudinal second mode may be distinguished at 4.5±0.2 Hz and a mode that looks like the second torsion mode may be found at 5.7±0.2 Hz. We can also well determine the first vertical mode at 9.3±0.2 Hz.

a)



b)

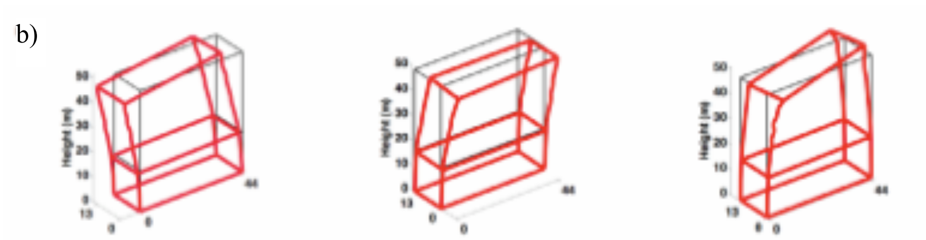


Figure 3. a) Spectrum (mean over the 8 datasets of the 6 first singular values of the PSD matrices) of the structure under ambient vibrations computed using the Frequency Domain Decomposition FDD (Brincker et al., 2001a). b) 3 first structural modes of the structure obtained using FDD (from left to right: longitudinal bending, transverse bending and torsion).

Comparing ambient vibrations and earthquake recordings.

To demonstrate the relevancy of the modes determined under ambient vibrations, we compare them to the resonance frequencies using earthquake recordings. For that purpose, we used an Auto-Regressive (AR) modelling of the structure (Dunand et al., 2006). We model each couple of base/top sensors (OGH1-OGH4, OGH2-OGH5 and OGH3-OGH6) by an AR filter obtained using the Linear Prediction method on the software Matlab. The top motion is first deconvolved by the base motion with a water-level method (Clayton and Wiggins, 1976) and the resulting spectrum is approximated by the best AR filter. A stabilization diagram using several numbers of poles in the AR filter allows estimating the confidence in the frequency and damping obtained for the first resonance frequency in each direction. The results are approximately the same for the three couples of sensor so that we keep only the median value for each earthquake (Fig. 4). We can observe a slight decrease (less than 2%) of the frequencies with increasing drift up to 10^{-5}. This tendency seems to follow a logarithmic scale and it would mean the frequency decreases in a logarithmic way with respect to the drift amplitude. This decrease may be due to the aperture of micro-cracks in the concrete that temporary decreases the stiffness of the structure and therefore the frequencies, as already mentioned by Dunand et al. (2006) using Californian strong motion data collected in buildings, but also due to the source of the shaking (Michel and Guéguen, 2010).

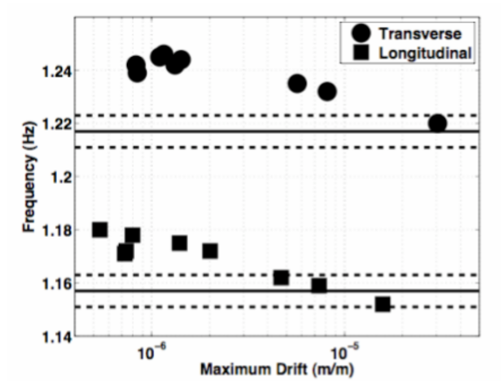


Figure 4. Resonance frequencies of the building in longitudinal and transverse directions for the nine earthquakes using AR modelling and plotted as function of the structure drift *Dm*. Solid line represents the frequency value obtained by the Frequency Domain Decomposition (FDD) under ambient vibrations (+/-uncertainties shown by dashed lines).

The frequency during the Vallorcine earthquake is approximately 2% lower than the frequency during the weakest earthquakes. The values obtained at low drifts are higher (2 to 3%) than the values obtained by the FDD method using ambient vibrations. The slight difference may be due to the system we study with the FDD and the AR methods: in the first case, we consider the flexible-base building including the soil-structure interaction while in the second case, the system considered is the fixed-base building. The modal parameters obtained under ambient vibrations are unscaled (Brincker et al., 2003), i.e. it is not possible to deduce the amplitude of the building motion with the only modal parameters. We need therefore a physical model integrating the modal parameters. As the masses are mostly concentrated at the floors in a building, we assumed a lumped-mass modelling for this structure. In this case, the Duhamel integral (Clough and Penzien, 1993) gives us the elastic motion of the structure at each floor {U(t)} assuming a constant mass along the stories [M], and knowing the vibration modes ([Φ] the modal shapes, {ω} the frequencies and {ξ} the damping ratios) and the motion of the ground U(t):

$$\{U(t)\} = [\Phi]\{y(t)\} + U_s(t)$$

$$\text{with } \forall j \in [1,N] \;\; y_j(t) = \frac{-p_j}{\omega'} \int_0^t U_s''(\tau) e^{-\xi_j \omega_j (t-\tau)} \sin(\omega'(t-\tau)) d\tau,$$

$$\omega_j'^2 = \omega_j^2(1-\xi_j^2) \text{ and } p_j = \frac{\{\Phi_j\}^T[M]\{1\}}{\{\Phi_j\}^T[M]\{\Phi_j\}} = \frac{\sum_{i=1}^{N}\Phi_{ij}}{\sum_{i=1}^{N}\Phi_{ij}^2} \text{ the participation factor of mode j.}$$

We consider that only the first bending modes provide energy, neglecting the torsion mode for the sake of simplicity. We assume then an 1D model so that we average the experimental modal shapes at each floor. It is possible to compute the motion at each floor for any deterministic earthquake scenario. This is of course a linear model, which suits only for moderate motions. Nevertheless, elastic modelling can be used to detect whether the building reaches the post-elastic state or not. The uncertainties of this model are only epistemic because the errors on the parameters used are quite low. The experimental values could be used to adjust a more complicated model, e.g. a 3D finite elements model (Ventura et al., 2003; Pan et al., 2004, Michel et al., 2009) but only few parameters of such a model can be accurately determined so that the modelling is still based on much a priori knowledge and does not bring much more information than the 1D lumped-mass model.

In order to test the relevancy of this model, we compare the motion obtained at the top of the structure during the recorded earthquakes with the corresponding modelling. The input motion is an average of the recorded motion at the ground floor of the structure. Even if usually there are four independent motions in a structure (Guéguen et al., 2005) (relative motion of the foundation, base rocking, torsion and structural drift), we observe for this building that the motion is essentially structural drift fitted by the modal model used in this study. We consider the four aforementioned parameters describing the motion (PTA, PTV, Iat, Dm) plus the duration of the building motion. The duration is defined here as the time between 5% and 95% of Arias Intensity. The accelerations are more often underestimated since the torsion mode is not accounted for the lumped-mass model considered here (Fig 5). Most of the error on PTV, Dm and duration are less than 20%. The Arias Intensity at the top is well reproduced except for the smallest earthquakes. Neglecting the torsion mode is certainly the strongest approximation in the model. The overall results are nevertheless satisfactory and they validate the simple modal modelling extracted from ambient vibrations and used to reproduce the building motion under moderate earthquakes.

Conclusions

In this paper, we show how the dynamic response in the elastic domain of existing buildings is obtained using ambient vibrations. Because of the development of new Operational Modal Analysis methods based on ambient vibrations, the comprehension and obtainment of the precise modal response of buildings can be used to predict the building behaviour under moderate earthquakes. The study is focused on the City-Hall building of Grenoble that presents the advantages to be permanently monitored. The first year of permanent accelerometric recording in the Grenoble City Hall completed with ambient vibration measurements at a full scale allows understanding better the dynamic behaviour of the structure. It is largely dominated by its first bending mode in each direction, including nevertheless a slight torsion mode. During the recorded earthquakes, the frequencies of the structure decreased of 3% with respect to the ambient vibration values. The decrease in frequency follows a logarithmic decay with respect to the drift of the structure. This decrease is slight enough to consider that the modal properties extracted from ambient vibrations are relevant in a large range of amplitudes, in the elastic behaviour domain of the structure. Assuming a 1D lumped and constant mass model, we used the experimental modal parameters to reproduce the motion of the building for moderate earthquakes, without any hypothesis on the structural design and materials. The building motion parameters like acceleration or velocity amplitude, duration, drift and energy are quite good reproduced with this simple model. Therefore, the response of a structure to moderate earthquakes can be easily predicted as soon as the intrinsic behaviour of the building under ambient vibrations is fairly good determined using experimental techniques. It allows calculating the inter-story drift for any moderate ground motion and then obtaining a first assessment of the integrity of the building. For example, in the case of the City Hall, the inter-story drift is maximal for the last floors of the building (above the precast slab) and especially in the transverse direction.

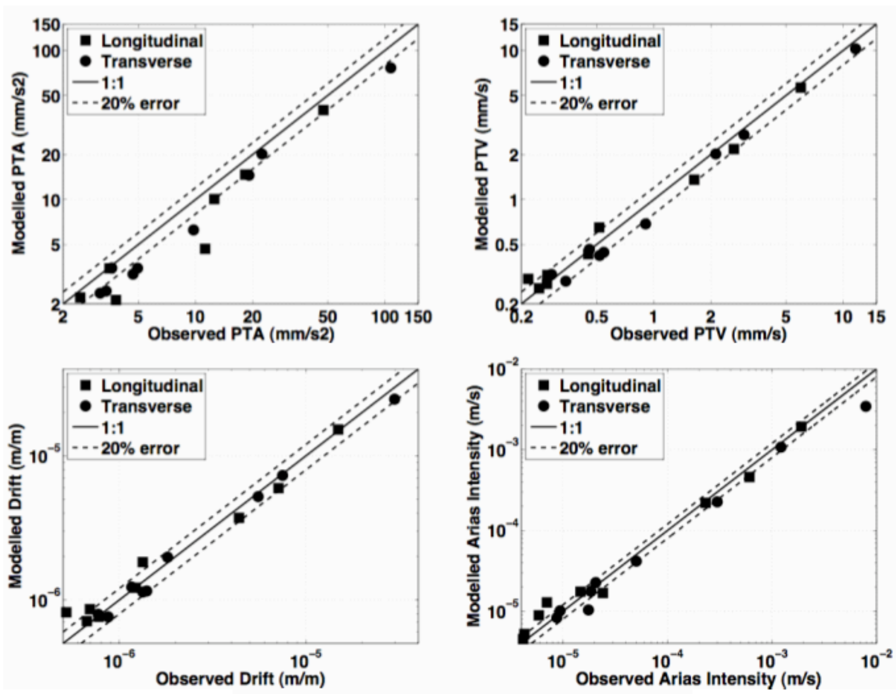


Figure 5: Comparison of the parameters (PTA, PTV, maximum drift, Arias intensity) computed at the building top using the lumped-mass model and the accelerometric recordings of the City Hall.

Assuming an inter-storey drift threshold for a given performance of the building (immediate occupancy in our case) as proposed by the FEMA, we can forecast whether the building will be damaged (or not) considering a deterministic earthquake scenario. Obtaining the dynamic elastic properties of existing buildings is therefore crucial for the estimate of the building motion under earthquakes. Fixing the elastic domain behaviour of existing buildings may be assumed as the first step of an exhaustive vulnerability analysis that generally explores the anelastic domain.

Acknowledgements

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