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Abstract

Seismic vulnerability in wide areas is usually assessed in the basis of inventories of structural parameters of the building stock, especially in high hazard countries like USA or Italy. France is a country with moderate seismicity so that it requires lower-cost methods. Ambient vibrations analyses seem to be an alternative way to determine the vulnerability of buildings. The modal parameters we extract from these recordings give us a 1D model for each class of building found in the study area. We then study the response of these models to realistic seismic excitations (*scenarios*) including site effects in order to determine a threshold acceleration sustained by this class of building which we interpret as a vulnerability index. The distribution of the classes in the city will lead to a vulnerability map.

In order to validate this method, we compare the modal parameters of a building in Grenoble (France) determined under ambient noise and during a stronger excitation: the demolition of a nearby bridge. A statistical study of recordings using time windowing gives uncertainties and leads us to conclude that the modal parameters are equal.

1 Introduction

In areas of low or moderate seismic activity, the effects of possible large earthquakes are usually explored through earthquake *scenarios*. One of the main parameters controlling the possible consequences of strong events is the ability of the building stock to resist to the ground motion. Different techniques are usually employed to assess the vulnerability of existing buildings which are usually considered as the most vulnerable. These methods were developed for area-wide data collection. Many of them are based on the inventory of structural parameters of the design collected by visual inspections and related to observational data of damage during past earthquakes (EMS98 [1], HAZUS [2], GNDT [3]). Nevertheless, these methods are not well-adapted in countries with moderate seismicity like France where no recent significant damages due to earthquakes have been observed. Indeed, they are generally used for the calibration of the vulnerability curves, accounting for the specificities of the structural design of each region.

Ambient vibration analysis is proposed as an alternative way to inspect buildings before or after an earthquake [4]. This fast and low-cost method is well-adapted to large-scale studies for which a large amount of buildings has to be instrumented. The reliability of ambient modal analysis in earthquake engineering has been validated by many comparisons between strong motion recordings and ambient noise where permanent instrumentation in buildings exists [5,6,7,8]. However, in most cases, these studies deal with eigen frequencies but not with modal shapes because of the limited scheme of permanent monitoring.

The in-situ assessment of the modal parameters can participate to:

1. the estimate of the damage level after an earthquake by considering the decrease of the fundamental frequency as function of the building integrity [7,8]
2. the estimate of the building vulnerability. In this case, we determine the modal parameters under ambient vibrations for each class of the typology found in the study area. It allows us to predict the storey drift of the structure under seismic input motion. The damage level can then be simulated for a strong ground motion *scenario* based on the maximum strain supported by each building class.

One of the most common critics usually done on the use of ambient vibrations in engineering structures is the very low level of vibration which cannot be compared to the building behaviour during earthquakes. In order to validate the evaluation of the modal parameters under ambient vibrations, we compare the modal parameters of a structure obtained under ambient vibrations and under vibrations produced by the demolition of a bridge located close to the experimented building. First, the building and the experiments are briefly described before the comparison of the modal parameters obtained with the two different natures of vibration. The 1D model derived from this analysis is then used to calculate the motion at each storey and deduce the stiffness matrix. This matrix can be interpolated to model all the buildings of a class in order to predict damage for strong motion *scenarios*.

2 Studied building

The building studied is a 9 storeys reinforced concrete (RC) frame structure located in the centre part of Grenoble of about 275m² surface area and 35m height. This building has been constructed just after World War II and it is typical of one of the most important class of buildings found in the urban zone of Grenoble. This building is part of a group of buildings which makes it difficult to measure modal parameters. It is classified in the European Macroseismic Scale (EMS98) [1] in type “Reinforced Concrete Frame Building” which corresponds to one of the most vulnerable class among the RC structures listed in the EMS98.

3 Recordings in the structure

3.1 Ambient noise

In May 2004, an experiment based on ambient vibration recordings was carried out. The station used is a Cityshark™ II [9], a user-friendly station dedicated to ambient vibration recordings and developed by the French Institute for Research and Development (IRD) and a local French company (LEAS). This station allows the simultaneous recording of 18 channels with a high time accuracy. In order to evaluate the total motion of the structure, an array composed of 6 three-component seismic sensors was installed in the building. The sensors are Lennartz Le3D-5s, with a flat response from 0.2 to 50 Hz. A reference sensor was installed at the top floor of the building for the experiment and the 5 others were installed as shown figure 1. The sampling frequency was set to 200 Hz. The sensors were oriented in the X-direction of the structure (Figure 1).

3.2 Collapse of the bridge

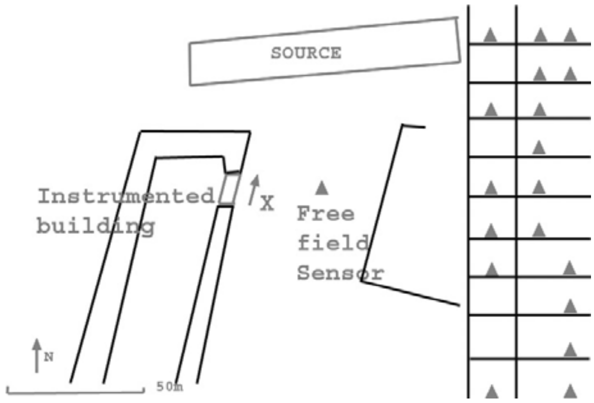

Figure 1: (left part) Localization of source, building and accelerometer (right part) Instrumentation scheme of the building for the bridge experiment and the ambient noise recording (2 sets of data)

The demolition of the bridge occurred July 17th 2004 in the framework of the construction of the new urban program. We instrumented the same building as previous with the Cityshark™ II station and the 6 Lennartz sensors (Figure 1). Sampling frequency was set to 100 Hz. In addition, a RefTek station with a CMG5 (broad band) accelerometer was placed on the free field, in front of the building in order to give a record of the source function. All sensors were about 40 m far from the bridge (Figure 1).

The instantaneous collapse of the bridge (source time about 5 ms) generated a seismic motion of relatively high

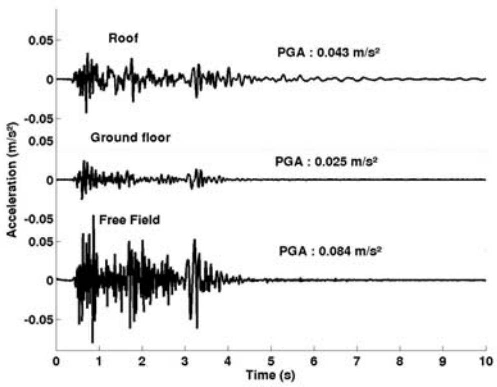

Figure 2a: Recordings of the bridge's collapse in the building and in free field

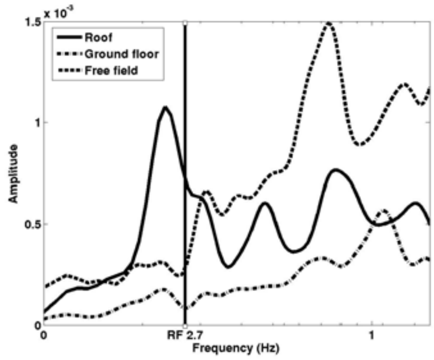

Figure 2b: Fast Fourier transform of the recordings of the bridge's collapse. RF means Resonance Frequency of the building obtained under ambient vibrations

frequencies (about 10 Hz). Figure 2 shows that the kinematic soil-structure interaction might strongly attenuate the upper frequencies. The frequency range of the source is far from the buildings' resonance frequencies. The Peak Ground Accelerations (PGAs) generated during the collapse are around 0.084 m/s² for free field and 0.025 m/s² for the ground floor. At the top of the building, the PGA reaches 0.043 m/s². This is a low value compared to the earthquake design regulation used in France (1.5 m/s² for zone Ib, e.g. Grenoble). Nevertheless, the PGA values are higher than those recorded under ambient noise and equivalent to PGA values obtained by forced vibrations system used in civil engineering.

4 Modal parameter determination and uncertainties

4.1 General Method

In order to calculate the modal parameters from ambient noise recordings, many techniques are available [10]. However, we need to evaluate uncertainties on modal shapes to know whether ambient noise and stronger excitation give the same results or not. Indeed, uncertainties are rarely discussed in ambient modal analysis [10,11]. In this paper, we decide to use the easiest method (peak picking) implemented with Matlab. In order to evaluate many modal shapes to perform statistics, we consider independent overlapping time windows of the signal at each floor (82 s for ambient vibrations, 5 s for the bridge's collapse). We need robust statistics to avoid phase troubles so that we calculate the median and the 5th and 95th percentiles of the amplitude of Fourier transform at the eigen frequency at each floor. By now, the origin of the time variation of the frequency values and the modal shapes is not well understood. There are two different parts of variation: a random part, especially for higher modes which are difficult to detect with accuracy and a part in phase at each floor which could be produced by a low unstationarity of ambient vibrations.

In the case of the bridge's collapse, we remove the source effect recorded at the ground floor in order to boil down to the output-only case. The same process as under ambient noise can then be applied.

4.2 Results

Two frequencies have been detected, the second one being not clearly identified especially under ambient vibrations. The fundamental frequency is 2.69 Hz with a standard deviation of 0.8 % under ambient vibration and 2.9 Hz (± 9 %) under stronger excitation.

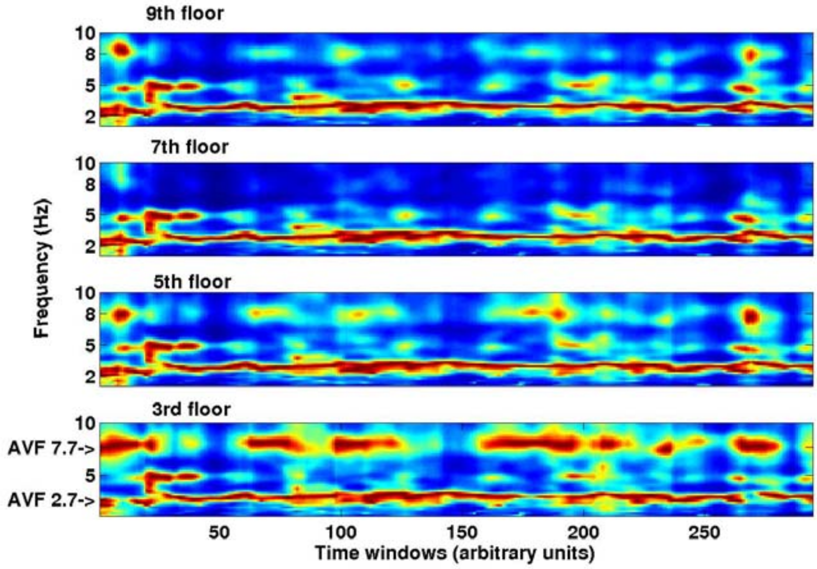

Figure 3: Spectrogram of the building's transfert function at different floors recorded during the bridge's collapse. AVF means Frequency determined under Ambient Vibrations.

The spectrogram (figure 3) shows the distribution of energy in different modes during the bridge's collapse. The second mode is clearly detected around 8 Hz and another one close to 4.9 Hz (± 9 %) may be interpreted as a torsion mode in the basis of the corresponding modal shape. The 7th floor is very close to the node of the second mode. By comparing the two experiments, this second mode is 8 Hz (± 4 %) and 7.71Hz (± 5.4 %) for the bridge's collapse and under ambient vibrations, respectively.

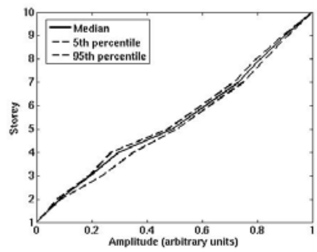

Figure 4a: First modal shape with uncertainties obtained under ambient vibrations

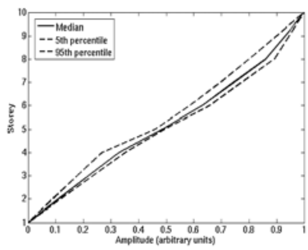

Figure 4b: First modal shape with uncertainties obtained from bridge's collapse

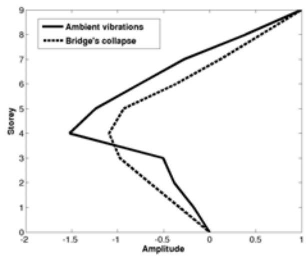

Figure 4c: Second modal shapes

The first modal shape (figure 4a and 4b) is well defined under ambient vibrations, better than under stronger excitation, in the opposite to the second modal shape (figure 4c) which is better constrained by the collapse experiment because of the frequency contain of the source (figure 2). However, in both cases, uncertainties are large for the second modal shape.

4.3 Stiffness calculation

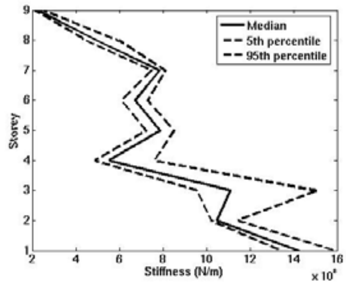

Figure 5: Stiffness at each floor with uncertainties

As we measure one point per floor, it is logical to adopt the lumped-mass idealization [12]. Then, following the sequence of eigen frequencies, we assume that the building behaves as a shear beam (in opposite to cantilever beam) [7]. This assumption means the floors are much stiffer than the walls, what is compatible with the frame structure of the building. Under this hypothesis, the stiffness matrix in the equation of motion is tridiagonal and the stiffness can be deduced at each floor from one modal shape, inverting the equation:

$$[K]\{\Phi\}=\omega^2\{\Phi\}$$

where K is the stiffness matrix, Φ a modal shape and ω the corresponding eigen pulsation. The result of this inversion from the first ambient vibration modal shape with uncertainties is presented figure 5. A lack of rigidity between the 3rd and the 4th floors is observed which needs further in-situ analysis to be explained. The decrease of stiffness with height is interpreted as the effect of the embedding in the other buildings.

5 Simple modelling of the building

The modal parameters we deduce from ambient vibration analysis allow us to calculate the motion of the building subject to earthquakes at each storey using the Duhamel integral [12] and the average strain per floor can be deduced. The damping ratio is evaluated by the random decrement technique implemented in GEOPSY [7,13], a freeware for geophysical signal processing developed in Grenoble. The damping values are 2.5 % and 7 % for the 1st and 2nd mode, respectively.

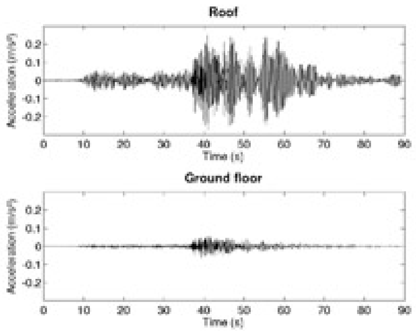

Figure 6: Modeling of Besançon earthquake in the building

The vibration input motion applied at the base of the structure corresponds to the seismic ground motion recorded by the French Accelerometric Network (RAP) in the Grenoble valley for the Besançon earthquake (03/23/04, Ml=5.1, 250km to the North). The ground motion used was recorded by a station located close to the tested building. This event has been felt by people in Grenoble but no damage occurred in the town. Indeed, despite a PGA of only 0.06 m/s², the frequency range of this earthquake excited well the buildings because of 3D site effects. They are induced by the 3D Y-shaped deep basin of Grenoble filled mostly with late quaternary post-glacial deposits. By setting up an elastic strain limit to 0.1 % [S. Hans, personal communication] and multiplying this motion, we find that the maximum acceleration elastically sustained [14] by the building is 1.3 m/s². Compared to the French seismic regulation for the building design (1.5 m/s²), this building can be considered as quite vulnerable. The same process can be easily followed with different earthquakes recorded in Grenoble to perform a statistical study. In addition, by testing several buildings of the same class of the Grenoble typology, we will be able to obtain a generic model by class using stiffness matrices which can be used to simulate the earthquake's effects on the whole town. Knowing the spatial distribution of each type, we will be able to map the vulnerability of the city. This work has started in Grenoble and will go on until summer 2005.

6 Conclusion

By taking the opportunity of the bridge's collapse sequence in Grenoble close to the building tested, we show that modal parameters extracted from ambient noise recordings, especially modal shapes, are the same than those obtained under a stronger excitation. The source of this stronger excitation was unfortunately (or fortunately) not so strong than expected in the frequency range of buildings but was nevertheless significant. We show that modal parameters are equal within measurement uncertainties. It would be interesting to compare the results obtained with peak picking with other identification methods. Moreover, we show how to deduce the stiffness from these parameters which can be a decision support tool for pre- and post-seismic evaluation. The reliability of this method in detecting damage due to an earthquake has still to be tested in damaged buildings.

In addition, using a simple modelling of the building, we deduce a threshold acceleration for elastic behaviour which can be interpreted as a vulnerability index. All this work has been done without any plan of the studied structure, which is a point to be noticed, because of the lack of this information for old buildings. By testing all the building classes found in the study area, this method allows to map the vulnerability at a large scale, as planed for Grenoble. Nevertheless, the modeling process we use is 1D, especially neglecting the first torsion mode. This mode seems to play an important role in stronger excitation of the building. The link between seismic ground motion and excitation of torsion modes has to be clarified, e.g. with the help of permanent instrumentation of buildings.

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