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Aftershock Monitoring of Wenchuan Earthquake for a Residential Masonry Building

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ABSTRACT: The purpose of this work is to obtain structural dynamic responses by exploiting vibration signal measurements produced by earthquake excitation. After the Wenchuan Earthquake in 12 May 2008, a residential building was selected to be instrumented with accelerometers by Research Center of Structural Monitoring and Control, Harbin Institute of Technology. This building has been damaged by the Wenchuan earthquake. It represents a rare case of an instrumented building that has been damaged, and thus can serve as a full-scale benchmark to evaluate and further develop structural damage detection and identification methods. More than thirty earthquakes occurred after the building was instrumented in that area, and 15 of them, which have been recorded, excited the building vibrating obviously. Both the earthquake excitations and structural dynamic responses are presented in this paper. With help of subspace-based modal identification algorithm, structural modal parameters, including frequency, mode shape and damping ratio were obtained from above data. The variety of structural modal parameters can be found under different earthquake excitations. Based on this work, farther vibration-based structural damage detection and safety evaluation can be applied on this structure, which also were discussed in this paper.

1 INTRODUCTION

During the last three decades, vibration-based methods have been proven useful for the detection and localization of structural damage, which are current problems in Structural Health Monitoring field (Natke, 1997; Fritzen, 2005). The fundamental principle upon which vibration-based methods are founded is that small changes (damage) in a structure cause behavioral discrepancies in its vibration response. The goal thus is the reliable detection of such discrepancies in a structural measured vibration response and their precise association with a specific cause (damage localization and quantification). This may be achieved by comparing a nominal structural model (representing the safety structure) with a corresponding current model (representing the structure in its current – unknown - condition). Thus the two most important elements of a vibration-based method are (a) the modal properties representing structural safety condition (b) the exact and strict algorithm to assess the changes in above parameters. A variety of vibration-based damage detection methods have been proposed. Doebling *et al.*(1996) provided an extensive review on this subject.

Up to now, most of these works are finished in laboratory by the shake table, excitation hammer, or implemented based on the numerical simulation data (Ni, 2006; Soyoz, 2008; Zapico, 2006). Some factors existing in the real full scale structure are usually neglected, for example the effects of noise, the soil et al. Moreover most of these methods are only suitable for the structures serving normally but not in catastrophic events, such as earthquakes and hurricanes. The rapid assessment after catastrophic events of critical structures like bridges, power stations, dams and gymnasia, is mandatory for the concerned government agencies. Therefore, there is a considerable demand for assessing the damage under earthquake excitation, particularly for large critical structures. But real earthquake response data recorded in full scale structures are rarely used.

A pre-stressed concrete box-girder bridge was instrumented in 1977 to record and study strong motion records. Kian Mirza (2006) analyzed 10 most significant earthquakes and introduced a procedure for seismic structural health monitoring to determine the status of the serviceability of the structure. This procedure is a combination of the damage index method and the structural analyses. Todorovska and Trifunac (2007, 2008a) installed a 16-channel seismic monitoring array consisted of a 13-channel structural array of force balance accelerometers on a six-story reinforced concrete structure located in El Centro, California. They have finished a sequel of works by using the vibration response of a damaged building to analyze the changes in the structural frequencies, which are estimated based on the Gabor transform. A structural health monitoring method based on changes in wave travel times was proposed using strong motion data by the same authors. Todorovska and Trifunac (2008b) also applied wave travel times method on a 7-storey-reinforced concrete hotel building instrumented by a seismic monitoring system to infer about local and global changes of structural stiffness. Chaudhary and Fujino (2008) employed acceleration data from an instrumented bridge during 16 seismic events to identify structural modal parameters and structural parameters, and presented a framework of performance evaluation of base-isolated super structure and pile-supported sub-structure.

The purpose of this work is to obtain structural dynamic responses by exploiting vibration signal measurements produced by earthquake excitation. After the Wenchuan Earthquake in 12 May 2008, a residential building was selected to be instrumented with accelerometers by Research Center of Structural Monitoring and Control, Harbin Institute of Technology. This building has been damaged by the Wenchuan earthquake. It represents a rare case of an instrumented building that has been damaged, and thus can serve as a full-scale benchmark to evaluate and further develop structural damage detection and identification methods. More than two hundreds of earthquakes occurred after the building was instrumented in that area, and 22 of them, which have been recorded, excited the building vibrating obviously. Both the earthquake excitations and structural dynamic responses are presented in this paper.

The objectives of this work are to obtain structural dynamic responses by exploiting vibration signal measurements produced by earthquake excitation. This paper is divided into two main parts; at first, the aftershock monitoring system was described. As the monitoring results, the seismic wave and structural responses were shown in detail too. Secondly, structural modal parameters, such as natural frequencies and mode shapes, derived for the structure by system identification analysis from above data were given.

The remainder of this paper is organized as follows: description and instrumentation of the instrumented building and the aftershock monitoring and results are presented in section 2. In section 3, the subspace-based modal identification is presented in detail. Results of modal identification are discussed in the section 4. Some conclusions are drawn in the last section.

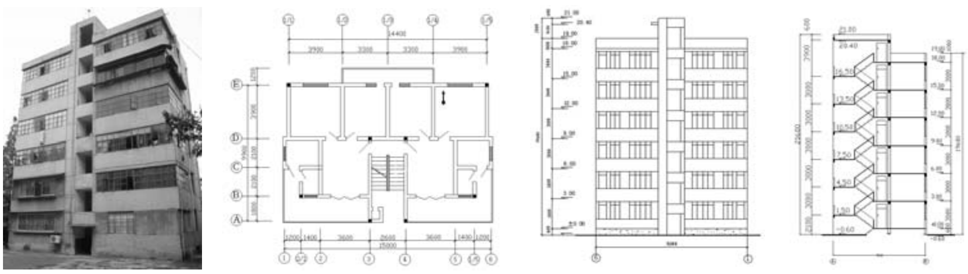
2 AFTERSHOCK MONITORING

2.1 Description and Instrumentation of the Building

The building investigated in this work, built in 1991, is a 6-story masonry structure in Guangyuan City, Sichuan Province of China (Figure 1). The location of Guangyuan City and distance from Wenchuan are shown in Figure 4. This building is an apartment for the staffs working in Guangyuan Earthquake Administration. It was slightly damaged during the 2008 Wenchuan earthquake. Obvious cracks can be found in the bearing wall, shown as Figure 2. The building was instrumented by Research Center of Structural Monitoring and Control, Harbin Institute of Technology at the end of September, 2008.

The instrumentation system consisted of an array of 6 uniaxial and 2 triaxial Caomu force-balance accelerometers. As shown in Figure 2, for the 1st floor, one triaxial accelerometer was placed. There is one uniaxial accelerometer, which is oriented horizontally, at each floor from the 2nd to the 6th one. On the roof of the building, there are one uniaxial and one triaxial accelerometer, which are used to measure torsion response.

The embedded accelerometers were characterized by a frequency bandwidth from DC to 120 Hz, a large amplitude range of ±2.0g and a wide dynamic range of 120 dB. These sensors were utilized in order to measure the free and forced-vibration responses under aftershock excitation. The sensors' signals were continuously recorded with a sampling rate of 100 Hz, using a 16-bit data acquisition card NI-6034E, made by National Instrument Inc, see Figure 3. Data acquisition software was developed by LabVIEW. All real-time information and data can be watched and downloaded by Internet in Harbin Institute of Technology, where is far away from Guanyuan City. Actually, all above sensors, transmission cables, data acquisition system and network constitute one integrated Online Structural Health Monitoring System.



(a) (b) (c) (d)

Figure 1. Overview of the apartment building

2.2 Description of Aftershock Monitoring

The local geographical situation of the building and the epicenter of the recorded earthquakes are shown in Figure 4*. After the building was instrumented, there are more than 40 aftershocks reported by the Sichuan Earthquake Administration. However, the building can not be excited by each earthquake to vibrate obviously. There are 22 earthquakes, which epicenters are near the building, were recorded by the accelerometers, shown as Figure 4. They are summarized in Table 1. The table includes the date, epicenter and magnitude of these earthquakes. Figure 5 shows the seismic excitation of record No. 8 and corresponding structural responses recorded by accelerometers. It should be note that there is something wrong in signal from channel 8. All analyses in current work will not use the data from this channel.

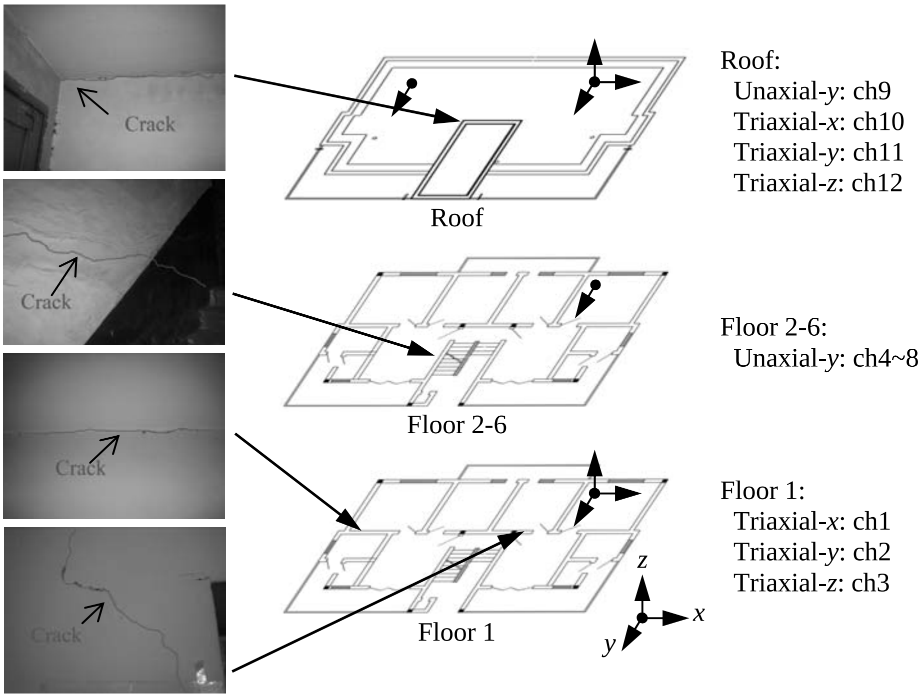


Figure 2. Damage situation of the building and the sensor locations

(a) The force-balance accelerometer (b) Data acquisition system

Figure 3. Sensor and data acquisition system

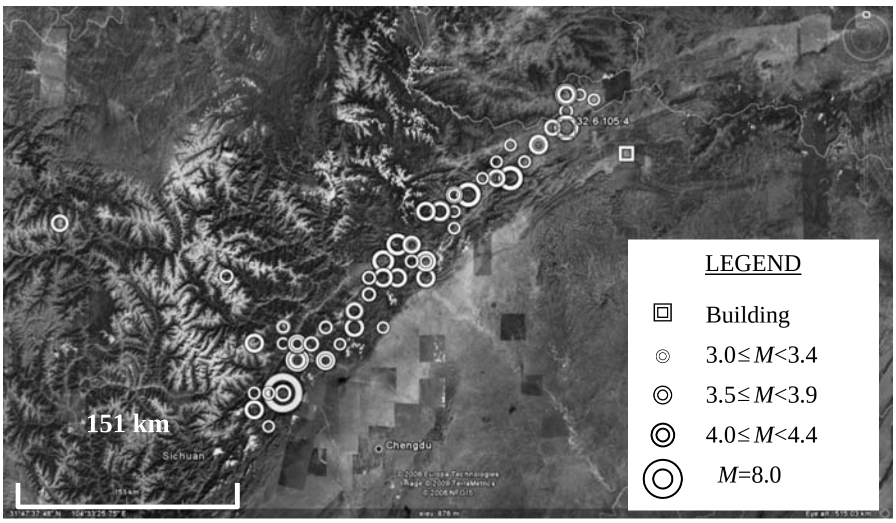


Figure 4. The local geographical situation of the building and epicenters of the recorded earthquakes

Table 1. Significant earthquakes recorded at the instrumented building (2008.10)

No.	Epicenter	Date & time	Magnitude	Longitude	Latitude	Epicenter Distance (km)
1	Qingchuan	03 Oct, 2008 07:08	3.0	32.6	105.3	52.4
2	Maoxian	04 Oct, 2008 20:10	4.5	31.8	104.1	177.9
3	Qingchuan	15 Oct, 2008 07:25	3.0	32.5	105.2	59.2
4	Qingchuan	16 Oct, 2008 03:25	3.0	32.4	105.1	68.5
5	Qingchuan	16 Oct, 2008 05:10	3.1	32.4	104.9	87.3
6	Qingchuan	18 Oct, 2008 16:40	3.2	32.4	105.1	68.5
7	Maoxian	21 Oct, 2008 15:25	4.1	31.7	104.1	182.7
8	Qingchuan	24 Oct, 2008 05:56	4.0	32.5	105.2	59.2
9	Qingchuan	25 Oct, 2008 23:05	3.3	32.7	105.4	48.3
10	Pingwu	02 Nov, 2008 04:36	3.1	32.3	104.9	88.1
11	Pingwu	04 Nov, 2008 20:43	4.5	32.1	104.5	130.5
12	Pingwu	04 Nov, 2008 21:15	3.9	32.1	104.5	130.5
13	Qingchuan	14 Nov, 2008 11:04	3.8	32.5	105.2	59.2
14	Qingchuan	14 Nov, 2008 14:33	4.3	32.8	105.4	56.1
15	Pingwu	16 Nov, 2008 06:59	5.1	32.2	104.7	109.5
16	Qingchuan	25 Nov, 2008 18:25	3.3	32.6	105.3	52.4
17	Qingchuan	27 Nov, 2008 22:36	3.8	32.6	105.4	43.7
18	Qingchuan	10 Dec, 2008 02:53	5.0	32.8	105.4	55.8
19	Pingwu	17 Dec, 2008 14:48	3.7	32.3	104.9	88.1
20	Beichuan	02 Jan, 2009 19:00	4.7	31.9	104.2	164.7
21	Pingwu	07 Jan, 2009 13:22	4.2	32.1	104.4	139.5
22	Qingchuan	08 Jan, 2009 13:49	3.6	32.6	105.3	52.4

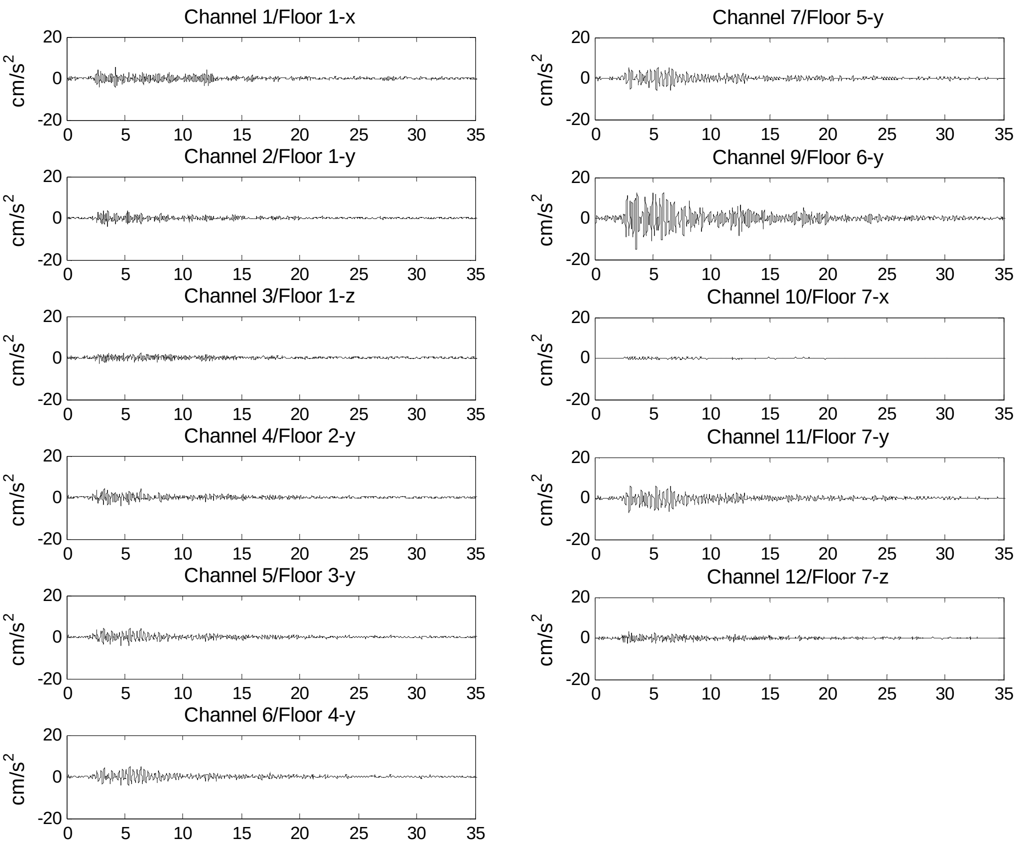


Figure 5. The time history of the No. 8 earthquake and the corresponding structural responses

3 SUBSPACE-BASED MODAL PARAMETER IDENTIFICATION APPROACH

In this study, the time-domain subspace-based modal identification method was used to extract the modal parameters (natural frequencies, mode shapes and modal damping) of the building.

We assume that the behavior of the building structure can be described by a dynamical system, and that the input forces can be modeled as a non-stationary white noise. This results in:

$$M\ddot{Z} + C\dot{Z} + KZ = v, Y = LZ \tag{1}$$

where *M*, *C*, *K* are the mass, damping and stiffness matrices respectively, (high dimensional) vector *Z* collects the displacements of the degrees of freedom of the structure; the external (non measured) force v is modeled as a non-stationary white noise, measurements are collected in vector *Y*, and matrix *L* indicates which components of the state vector are actually measured. The modes or eigenfrequencies denoted generically by μ, the eigenvectors ϕ_μ, and the mode shapes denoted generically by ψ_μ, are solutions of:

$$\det(\mu^2 M + \mu C + K) = 0, (\mu^2 M + \mu C + K)\phi_\mu = 0, \psi_\mu = L\phi_\mu \tag{2}$$

Sampling model (1) at rate $1/\tau$ yields the discrete time model in state space form:

$$\begin{cases} X_{k+1} = FX_k + V_{k+1} \\ Y_k = HX_k \end{cases} \tag{3}$$

where the state and the output are:

$$X_k = \begin{pmatrix} Z(k\tau) \\ \dot{Z}(k\tau) \end{pmatrix}, Y_k = Y(k\tau) \tag{4}$$

The modal parameters defined in (2) are equivalently found from the eigenstructure $(\lambda, \ \varphi_\lambda)$ of the state transition matrix F:

$$e^{\tau\mu} = \lambda, L\Phi_\mu = \phi_\lambda = H\varphi_\lambda \tag{5}$$

Eigenvectors are real if proportional damping is assumed, that is $C = \alpha M + \beta K$. The λ's and ϕ's are pairwise complex conjugate.

The basis for the subspace-based identification method is the fundamental factorization:

$$H_{p+1,q} = O_{p+1}C_q \tag{6}$$

where $H_{p+1,q}$ is the Hankel matrix built with measured covariances, and O_{p+1}, C_q are respectively the observability and controllability matrices of the system. They can be obtained from a singular value decomposition of above Hankel matrix, and then the eigenvalue and eigenvector of system. A complete description can be found in related references (Overschee, 1994).

4 BUILDING IDENTIFICATION RESULTS AND DISCUSSIONS

The modal identification was performed on above 22 records. Figure 6 shows the time histories of structural response in the sixth floor under the 8th seismic excitation. For investigating the effect of different amplitude earthquake record to the modal parameters, several more significant seismic responses were divided to three parts as shown in Figure 6 (No. 2, 8, 15, 18 and 21). All identified parameters for 29 segments of data are listed in Table 2, and plotted in Figure 7. As stated above, the building has been damaged during the Wenchuan earthquake. It can be concluded that the structural stiffness might change under different seismic excitations, especially the great ones. Therefore, structural modal parameters are also varying as shown in Figure 7. Moreover, the frequencies should be correlative with the amplitude of structural vibration, which affect structural stiffness. Figure 8 shows the relationship between the frequencies and the acceleration amplitude of the top floor. It seems the greater vibration lead to more stiffness reduction, and then more decrease in frequencies. However this only a straightforward and simply analysis, further analysis on these signals should be implemented, such as with help with the finite element model and time-frequency domain analysis tools. Here three kinds of methods are proposed to investigate this problem, the first is time-frequency analysis with wavelet transform, the second is to employ damage detection methods by using mode shapes, the third is to identify the change in hysteresis curve of the structure, and detect the structural damage.

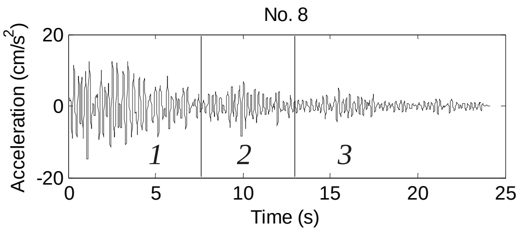


Figure 6. Typical structural responses of floor 6 under each seismic excitation

Table 2. The identified frequencies for all records

No.	Mode 1 (Hz)	Mode 2(Hz)	No.	Mode 1(Hz)	Mode 2(Hz)	No.	Mode 1(Hz)	Mode 2(Hz)
1	3.4766	4.6779	11	3.4194	4.6407	21	3.2574	4.6310
2	3.3881	4.6180	12	3.4032	4.6585	22	/	4.5769
3	/	4.5912	13	3.3501	4.6736	23	3.2994	/
4	3.3345	4.6076	14	3.3868	4.6896	24	3.3824	/
5	3.2158	4.5825	15	3.3831	4.5947	25	3.3594	4.6865
6	3.2823	4.6378	16	3.3111	4.6699	26	3.3871	4.6338
7	3.3321	4.7557	17	/	/	27	/	4.7158
8	3.3537	4.5182	18	3.3571	/	28	3.4014	4.6633
9	3.3155	4.4194	19	3.3855	4.5765	29	3.3501	4.7818
10	3.2866	4.4926	20	3.3462	4.6676			

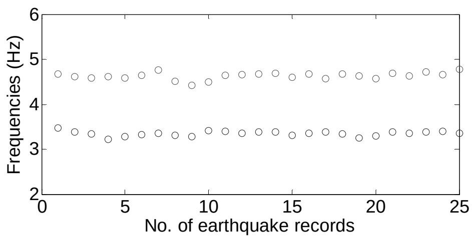


Figure 7. Modal identification results

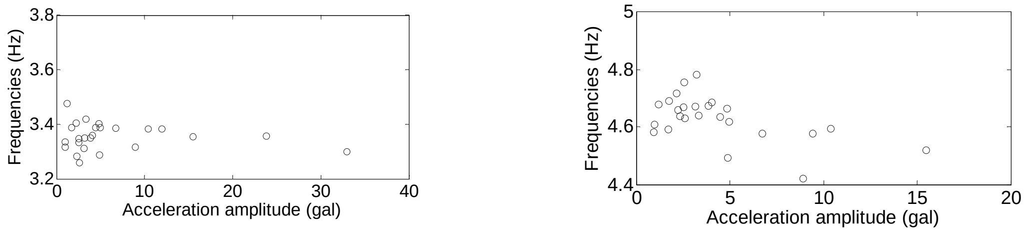


Figure 8. Relationship between frequencies and acceleration amplitudes.

5 CONLOUSIONS

This study presents seismic monitoring the results from a 6-storey residential masonry building instrumented with a SHM system, and the results of the modal identification based on a time-domain identification technique.

Two modal frequencies are extracted from the structural response under seismic excitation. From the direct results of modal identification, it is easy to find the change in frequencies, but hard to determine the severity of the damage. Further analysis such as damage detection and safety evaluation of the structure will be carried out.

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