Use of Ambient and Forced Vibration Tests to Evaluate Seismic Properties of an Unreinforced Masonry Building Rehabilitated by Dampers

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SUMMARY:
This paper presents the identification and evaluation of the seismic properties of an old unreinforced masonry building by ambient and forced vibration tests. The building is three storied with irregular shape located in Algiers (Algeria) and was rehabilitated by hysteretic dampers system. Ambient vibrations were measured before and after rehabilitation. While, a series of low amplitude steady state harmonic forced vibration tests were conducted after rehabilitation using eccentric mass shaker. The resonant frequencies, mode shapes and damping coefficients as well as stresses in the steel braces have been evaluated and defined. It was shown that the dynamic behaviour of the masonry building, even if not regular and with deformable floors, can be effectively represented.

Keywords: Unreinforced masonry buildings, ambient vibrations, forced vibrations

1. INTRODUCTION

Unreinforced masonry buildings have long been recognized to perform poorly under earthquake excitation. This deficient performance was clearly demonstrated in several past major earthquakes in Algeria such as the 1994 Beni-Chougrane earthquake (Naili, 1996) and the 2003 Boumerdes earthquake (Oussalem *et al.*, 2003) or over the world such as the 1989 Loma Prieta earthquake (Bruneau, 1994) earthquake. In accordance with their poor performance in earthquakes, an understanding of the dynamic behaviour of unreinforced masonry buildings when subjected to seismic excitation is of major interest in many seismically active countries such as Algeria. In Algeria, masonry buildings are a typical residential constructions type found in most Algerian urban centres. This construction, built mostly before the 1950s by French contractors, is no longer practiced (Farsi *et al.*, 2002). Buildings of this type are typically 2 to 6 stories high. The slabs are wooden structures or shallow arches supported by steel beams, filled with earth materials. Masonry walls, usually 400 to 600 mm thick, have adequate gravity load-bearing capacity; however, their lateral load resistance is very low. As a result, these buildings are considered to be highly vulnerable to seismic hazard.

While ambient and forced vibration tests are usual applied techniques for reinforced concrete or steel buildings to understand and identify their dynamic behaviour, less is known about masonry buildings. The dynamic behaviour of old masonry buildings differs from that of concrete or steel buildings, due to the historic construction typology, leading to walls and floors not rigidly attached to each other. Hence, local modes are more evident with respect to frame buildings (De Sortis *et al.*, 2005). For the same reason, usually the dynamic forced response depends on the shaker location and applied force amplitude. Therefore, it is essential to determine dynamic parameters such as natural frequencies, damping factors and mode shapes, which are typically obtained using modal identification techniques by conducting ambient or forced vibration tests (Abdul Karim *et al.*, 2008). Ambient vibration can be from sources such as wind, waves, pedestrian or vehicles, with the vibration not controlled but instead considered as a stationary random process. Thus, the response data from the structure alone is used to estimate the dynamic parameters (Shabbir, 2008). In contrast, forced vibration testing provides a known input force over the frequency bands of interest, which can be achieved by the excitation input motions. Thus, the dynamic characteristics of structures can be explicitly recognized.

The objectives of the testing for our masonry building were first, to investigate the change of natural frequencies of the building before and after strengthening by ambient vibration test and second, to investigate the dynamic behaviour of the building after strengthening at resonant conditions (harmonic forced vibration) by forced vibration test. Based on forced vibration techniques, the resonant frequency curves, mode shapes and damping coefficients as well as stress distribution at strengthening system could be defined. These parameters are strongly related to prediction of dynamic behaviour of the structure under earthquake excitation.

2. DESCRIPTION OF THE BUILDING AND THE RETROFITTING SYSTEM

The aimed building was constructed in 1908 during the French colonization period, and now is used as a residential building. The building has an irregular shape consisting of basement, ground floor, two floors and tower, representing a part of third floor. The in plane dimensions of the building are of length 22 m and 17.75 m. The structural system is composed by masonry bearing walls, with mean thickness of 50cm. The floors were built with hollow clay elements supported by steel beams interspaced at 50cm. The steel beams are simply supported by the bearing walls. A schematic view of the structural and strengthening system of the building is shown in Figure 1.

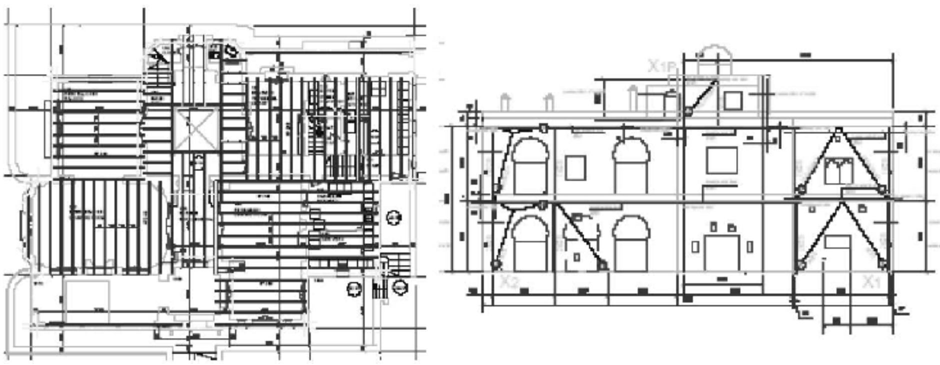


Figure 1. Schematic view of the structural and strengthening system

There were some visible cracks, which happened during the past 2003 Boumerdes earthquake. It was obviously that some repairing and strengthening solution should be applied. The retrofitting system DC-90 consists of several steel elements such as anchors, prestressing bars, diagonal bracings and yielding type dampers (Skuber *et al.*, 2006). Figure 2 shows details for the connection of the damper, diagonal brace and vertical bar. The appearance of the building after retrofitting is presented in Figure 3.

Figure 2. View of the a connection detail for DC-90 system

(a) (b)

Figure 3. View of the building after retrofitting: (a) S-W façade, and (b) N-E façade

3. TEST EQUIPMENT AND MEASUREMENT METHODOLOGY

The building dynamic behaviour has been monitored by three different types of instrumentation: seismometers for ambient vibration measurements, accelerometers for forced vibration measurements and strain gauges for recording the strains (stress) in steel bracings of the DC-90 system.

3.1. Ambient Vibration Test

The ambient vibration testing methodology is based on ambient excitation such as wind. The very sensitive seismometers are capable to catch the produced microtremors which are a random type of signal, consisting of excitation frequencies in broad frequency range, enough to excite several modes of structural vibration. The measurements performed in selected 15 points at level III, as shown in Figure 4, give some general information about natural frequencies of the building after retrofitting. The ambient vibration equipment consists of City Shark I station (digital recorder) coupled by Lennartz seismometers type LE-3D. One by one, fifteen points have been measured in two orthogonal directions at level III. The objective was to give a first estimation of the natural frequencies before retrofitting of the building, and to estimate the position of the centre of torsion where the shaker will be placed for forced vibration test.

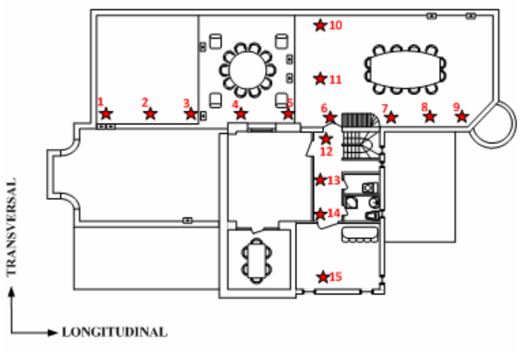


Figure 4. Measurement points position on level III for ambient vibration test.

3.2. Forced Vibration Test

The forced vibration testing methodology is based on resonant concept. By the application of a dynamic harmonic force on the top of the building, it is possible to excite the resonant frequencies of the building, if the frequency of the force is equal to one of the natural frequencies of the building. The frequency of the force can be gradually changed in small steps within the range of 0.5-16.0 Hz. The resonant state is reached when the acceleration response at the measurement point become maximum and then decrease even the frequency of the force still increase. On this manner, frequency response curves can be obtained for each orthogonal direction and torsion. The forced vibration equipment, shown in Figure 5, consists of an eccentric mass shaker for excitation with a harmonic sinusoidal force within the frequency range 1-15 Hz as well as signal recording equipment: data acquisition system 16 channels - National Instruments-USA, Kistler accelerometers 5g, and signal amplifier- Kistler-USA, for accelerometers (8 channels), signal amplifier-Kyowa, for Kyowa strain-gauges KFC-5 (8 channels). A labtop computer was used to process the digitised data. The measurement points for level III and level IV is shown in Figure 6.

Figure 5. Eccentric mass shaker for excitation of harmonic force

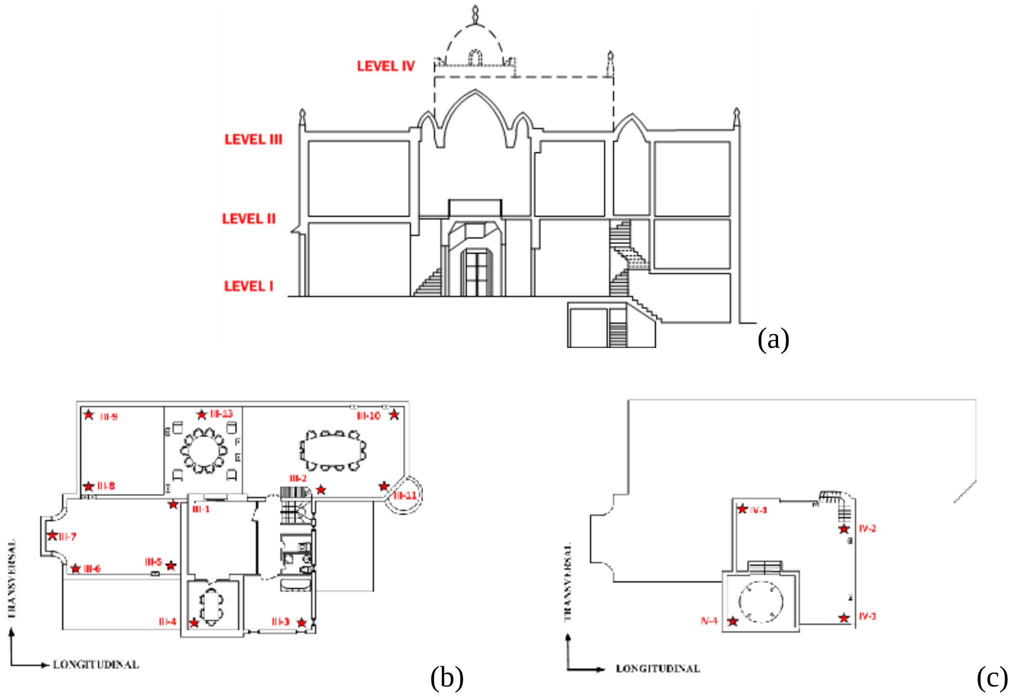


Figure 6. Plan view of the building and floor levels with measuring points of accelerometers: (a) Elevation view, (b) Third floor, (c) Fourth floor

4. AMBIENT VIBRATION TEST RESULTS

Fourier amplitude spectra recorded in measurement point 4 before retrofitting is shown in Figure 7 for longitudinal and transversal directions, while thus recorded after retrofitting by dampers is shown in Figure 8. Comparative presentation of the frequencies is given on Table 1. The comparison between natural frequencies given by ambient vibration test before and after retrofitting shows that they become higher after retrofitting for about 5%.

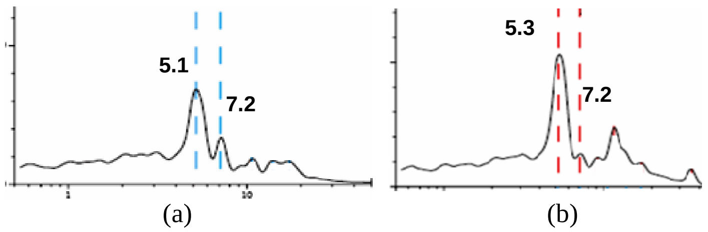


Figure 7. Fourier amplitude spectra before retrofitting: (a) Transversal direction, (b) Longitudinal direction

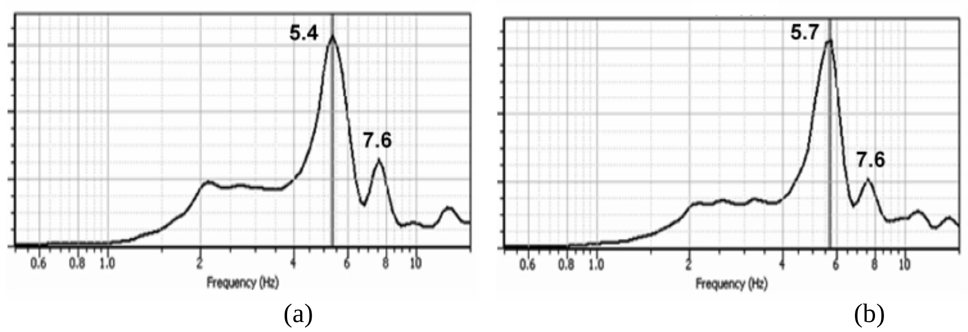


Figure 8. Fourier amplitude spectra after retrofitting: (a) Transversal direction (b) Longitudinal direction

Table 1. Natural frequencies of the building before and after retrofitting

Direction	Natural Frequency (Hz)	
	Before retrofitting	After retrofitting
Transversal	5.1	5.4
Longitudinal	5.3	5.7
Torsion	7.2	7.6

The fundamental vibration mode shape obtained based on ambient vibration test after retrofitting is shown in Figure 9. The story peaks were normalized for the top peak.

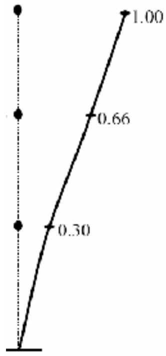
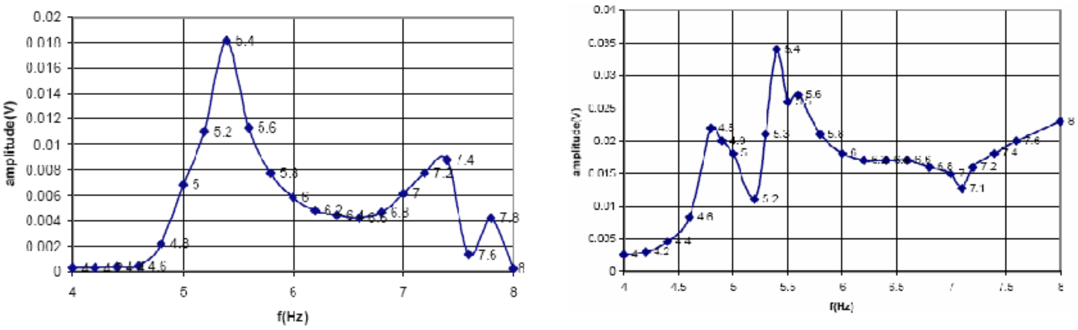


Figure 9. Mode shape in the longitudinal direction obtained by ambient vibration test

5. FORCED VIBRATION TEST RESULTS

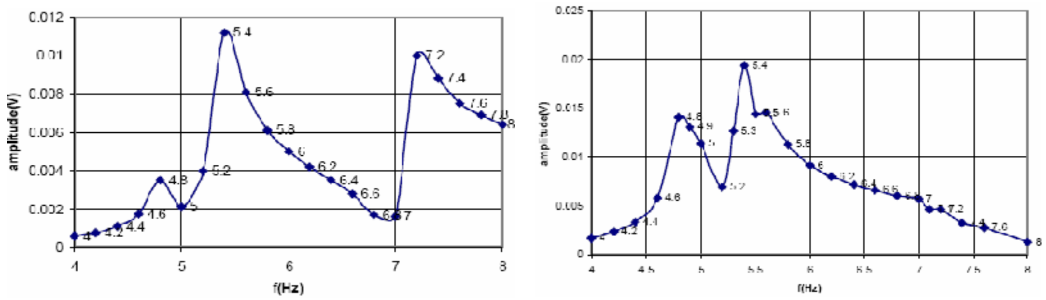
5.1. Frequency Response Curves

Frequency response curves are obtained by recording the acceleration response at particular points on level III and IV in two orthogonal directions (Longitudinal and transversal directions). The frequency response curves for recording points III-1 and III-10 are given in Figure 10 and Figure 11, respectively. The resonant frequencies defined by forced vibration method as can be seen from resonant frequency curves, are smaller than the ambient frequencies for about 3-5 %, which is close to the original state before retrofitting (Table 2). It can be concluded that the retrofitting of the building does not change the dynamic properties of the building. This is mainly due to the high stiffness of the masonry walls, in which, the inserted steel bars do not change their stiffness.



(a) (b)

Figure 10. Frequency Response Curve for point III-1: (a) Transversal excitation, (b) Longitudinal excitation



(a) (b)

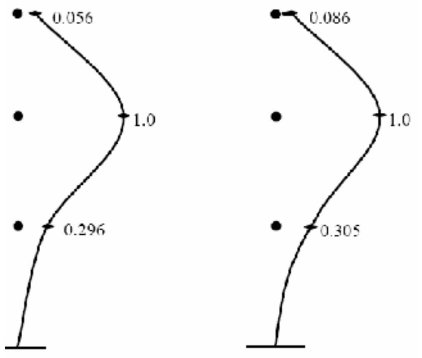
Figure 11. Frequency Response Curve for point III-10: (a) Transversal excitation, (b) Longitudinal excitation

Table 2. Natural frequencies of the building by ambient and forced vibration tests

Direction	Natural frequency (Hz)		
	Ambient vibration		Forced vibration
	Before retrofitting	After retrofitting	After retrofitting
Transversal	5.1	5.4	4.8
Longitudinal	5.3	5.7	5.4
Torsion	7.2	7.6	7.2

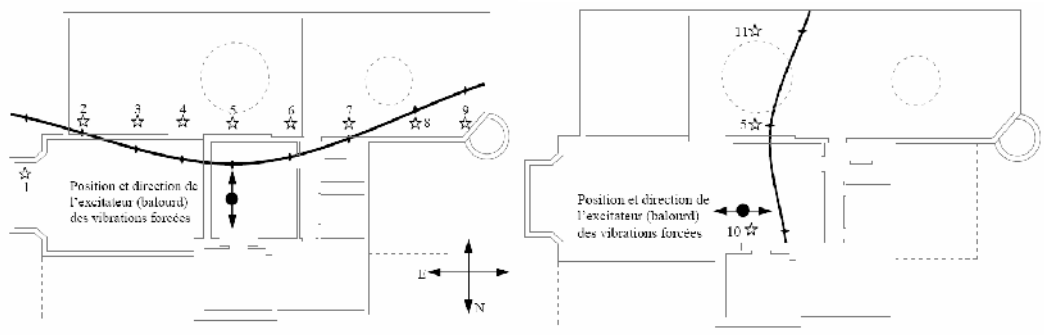
5.2. Plan Mode Shapes

The vertical vibration mode shapes obtained based on forced vibration test is shown in Figure 12. The in-plane vibration mode shape of the second story where the shaker was placed are illustrated if figure 13 for both transversal and longitudinal direction, respectively.



(a) (b)

Figure 12. Vibration mode shapes by forced vibration test (a) Transversal excitation (f=4.8 Hz), (b) Longitudinal excitation (f=5.4 Hz)



(a) (b)

Figure 13. In-plan vibration mode shapes by forced vibration test (a) Transversal excitation (f=4.8 Hz), (b) Longitudinal excitation (f=5.4 Hz)

5.3. Damping Coefficients

As far as damping coefficients concerns, they are defined from frequency response curves based on half power method. Table 3 shows the damping ratios as a percentage of critical damping corresponding to some measured points. The damping ratios are ranging between 2.7-5.8 %. This is rather high damping, which is good for dissipation of the energy during earthquake. These values should be much higher when DC-90 dampers become active when lateral displacements reach 1-5mm during earthquake. For this low level of excitation by force vibration, activation of the dampers is not expected.

5.4. Spatial Vibration Mode Shapes

The main objectives of forced vibration test were to define the resonant frequencies, damping coefficients and mode shapes of vibration of the building under resonant conditions. Having in mind the irregular shape of the building (unsymmetrical in plane), the torsional effects have been expected. To record such effects, two orthogonal horizontal components at each measuring point have been measured: one in direction of excitation and other in direction transversal to excitation force (Tashkov and Krstevska, 2007). Figures. 14, 15 and 16 show the spatial mode shapes for three defined resonant frequencies. It is obvious that torsional effect is present more-less in all three mode shapes which means that the modes are coupled i.e. for any excitation direction and frequency near resonant, the structure will vibrate torsionally. The most intensive vibration appears under the frequency 5.4Hz. It is visible from the frequency response curves and peak acceleration recorded at characteristic points of the building.

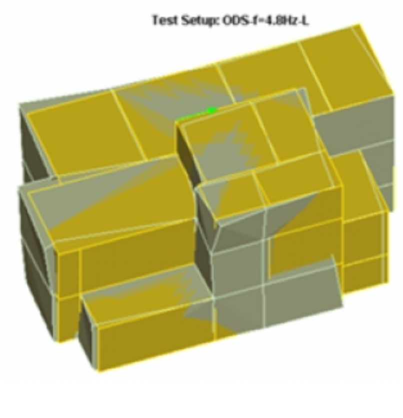


Figure 14. Vibration shape of the building at resonant frequency f=4.8Hz by excitation in the transversal direction.

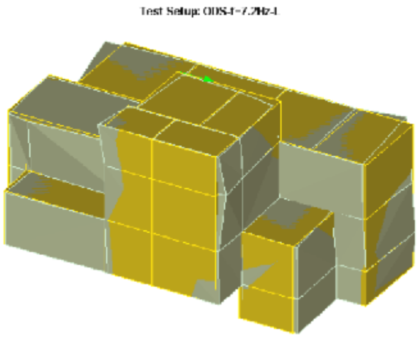


Figure 15. Vibration shape of the building at resonant frequency f=5.4Hz by excitation in the longitudinal direction.

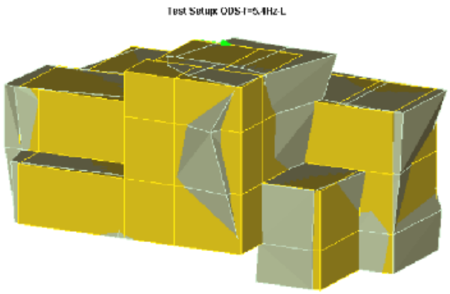


Figure 16. Vibration shape of the building at resonant frequency f= 7.2 Hz by excitation in longitudinal direction

6. CONCLUSIONS

Based on experimental testing of the masonry building by ambient and forced vibration methods, the following summarized results are obtained:

The first set of fundamental frequencies of the building is: transversal direction f1= 4.8 Hz, longitudinal direction f2 = 5.4 Hz and torsion 7.2 Hz. The vibration of the building at resonance condition is of the same intensity in longitudinal and transversal directions. For both excitation directions, all three frequencies are excited i.e. the building vibrate torsionally with coupling effect between the modes.

The vibration effect produced by forced vibration test was rather small comparing to real earthquake excitation conditions. The capacity of the shaker was much bigger than it was used, but because of safety precaution, higher excitation force was not applied.

The damping of the structure obtained from frequency response curve based on half-power method ranges between: 3-6 % of critical damping even under low amplitude vibration level. For realistic earthquake conditions it could reach much higher level considering the presence of the DC-90 dampers. At the excited level of vibration (1%g) the dampers have not been activated.

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