Seismic Rehabilitation of an Ancient Masonry Infill Steel Frame Building

Nouredine Bourahla [1]
Salim Tafraout [2]
Tahar Boukhamacha [2]

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ABSTRACT

Ancient buildings constructed in urban areas, particularly in Algiers, are typically 4 to 6 storey high and are made of stone masonry walls or infill light steel framing. These types of buildings are reputed to be vulnerable to seismic effects.

This paper presents a study on the renovation and required seismic upgrading of a 100 year old masonry infill steel frame building located in the centre of Algiers. The building is to be renovated for use as a modern art museum. The structure primarily consists of a light steel structure made of riveted steel trusses and columns having thick stone and brick masonry walls along its perimeter. The basement floor is made of shallow arches supported by steel beams (jack arch system) and the upper floors are wood-framed diaphragms. The building endured several moderate earthquakes that occurred in proximity to Algiers and as well sustained no significant damage from the Boumerdes earthquake (M 6.8) that occurred in 2003. The structure was numerically simulated using 3D finite elements models. The data, obtained from an extensive program of non-destructive and destructive tests on the constituent materials, were introduced into the numerical models and a series of ambient vibration tests together with modal analyses were performed to validate the mathematical models. A linear elastic analysis was carried out on the calibrated numerical model of the structure using the most recent elastic spectrum of the Algerian seismic code (RPA99 rev.2003).

Results of load combinations helped identify critical regions and seismic deficiencies. On the basis of these findings upgrade strategies and a solution for strengthening the structure are proposed.

KEYWORDS

Masonry strengthening, Ambient vibration, Structural assessment, Seismic vulnerability

[1] Saad Dahlab, Blida University, Civil Eng. Dept, Blida, Algeria 09000, Phone +213 25433939, Fax +213 254339393, nbourahla@mail.univ-blida.dz

[2] SCTE, Division Etudes, Algiers, Algeria, Phone +213 21 552895, Fax +213 21404920, scte_algiers@yahoo.fr

1 INTRODUCTION

In seismic prone areas, structural masonry is seldom used for new buildings since most collapses and deaths in recent earthquakes are due to inadequate performance of unreinforced masonry buildings. However, most of ancient buildings constructed in those regions are made of stone or brick masonry walls or infill light steel framing in which masonry panels play dominant role in resisting lateral forces. Research on the seismic behaviour of masonry structures is nowadays almost entirely dedicated to existing buildings and to the issues related to assessment and reduction of their seismic vulnerability [Magines G. 2007]. Because of different degrading agents, old masonry buildings become even more fragile and need to be strengthened. The determination of the material characteristics in terms of stiffness, strength and energy dissipation capacity (cyclic behaviour) is required to assess the actual resistance capacity and to design an efficient retrofit scheme [Bourahla & al. 2002]. In this context fiber reinforced polymer (FRP) materials offer viable solutions to solve or lessen the effects of overloading. Extensive research work investigated the seismic behaviour of rettrofitted masonry structures both analytically and experimentally [Triantafillou T. C. 1998, Tumialan G. Et al. 2001, Elgawady M. 2006, Shrive N. 2006]. This paper focuses on the structural diagnostic of an old masonry infill steel frame to identify the structural degradations and assess the overall dynamic and damping characteristics using ambient vibration testing. On the basis of the dynamic analysis, critical zones were identified and a strengthening technique based on fibre-reinforced polymers was adopted.

2 DESCRIPTION OF THE BUILDING

The edifice is an ancient building constructed in 1909 and intended to be used as a modern art museum. The construction is an L shaped four storey building located in the centre of Algiers. It comprises two patios in the middle with a roof incorporating five domes made of steel frames with glass infill. A 16 m height minaret is located at one corner of the building (Fig. 1).

Figure 1. Interior and exterior views of the building.

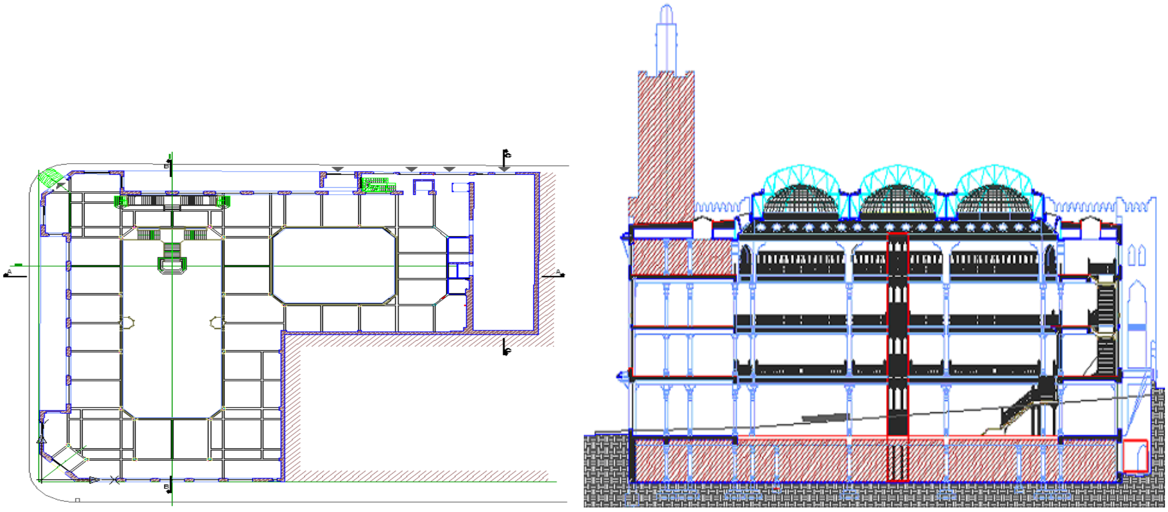

Figure 2. a- Plan view of the building b- Elevation view of the building

The edifice is supported by riveted light steel framing with peripheral stone/brick masonry walls of 90 cm thick used as a structural element to resist horizontal forces and part of the vertical loads. These walls are perforated by numerous window and door openings.
The slender steel columns are embedded in circular micro concrete sections to enhance their stability performance.

The building withstand several moderate earthquakes that occurred in the vicinity of Algiers and recently a major far field earthquake that occurred in Boumerdes 2003 about 40km away. An investigation of the building was carried out by a multidisciplinary engineering team. Beside the classical tests for material characteristics identification, a special attention was particularly made to investigate the building physically in search of any imprint the earthquakes might have left. The structural damage consists almost exclusively of widespread corrosion observed on certain steel elements because of humidity in areas subjected to water leak and exposed to sea environment. (Fig. 3).

Figure 3 a- Typical steel element corrosion b- column cross section

Damage inflicted by earthquakes is insignificant. It is thus somewhat extraordinary for such type of old building ---especially one with very tall stories, no substantial cross walls, a spacious multi-story interior sanctuary space and an irregular domed and gabled roof --- to resist the seismic activity for more than a century with almost no damage. On the basis of our studies, we conclude that certain specific dynamic characteristics of the structure and the exceptionally high material quality are largely responsible for this performance.

3 AMBIENT VIBRATION TESTING

The assessment of the structural resistance of existing constructions uses often mathematical models whose parameters can hardly be precisely estimated by analytical procedure only. Therefore, the elastic, mass and damping characteristics of the structure to be assessed must be known to a sufficient degree of accuracy in order to evaluate the actual structural capacity of the construction. The elastic dynamic properties, particularly the natural frequencies and the corresponding mode shapes are a combined measure of the structural characteristics of the construction. These model characteristics can be successfully estimated, especially in elastic range, using the well known ambient vibration testing. In this paper we present briefly the main issues pertaining to this particular modal testing; FRF measurement techniques, testing procedure, and modal parameter estimation method.

For this particular case preliminary modal analyses were first carried out and the fundamental modes were predetermined. On the base of these results optimum sensor locations were chosen nevertheless additional measurement points were also included to take account of any other modes that were not predicted by the analytical model. Measurement near the nodal point of any of the modes will omit that particular mode and aliasing effect is to be prevented by avoiding intersection regions of the fundamental modes to be identified.

The tests were performed using three degrees of freedom seismometer type Lennartz electronic (Le3Dlite) and a data acquisition system type City Shark II. The measured signals were processed using the GEOPSY program [Wathelet 2005] capable to perform most of the signal processing operations for the analysis of ambient vibration data. The sensors were located and oriented according to the previously defined test programme. The recording time for each sequence was set to 10 mn and found to be largely sufficient to obtain smooth transfer function curves. In total 24 measurement points were performed. Figure 4 shows the locations and the orientations of the sensors on the top floor.

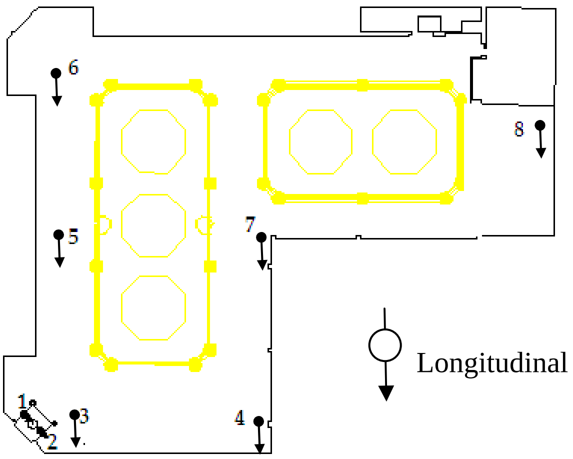

Figure 4. Locations and orientations of the sensors on the roof and the minaret

The natural frequencies of the structure were simply identified using a “peak cursor” on the Frequency Response Functions (FRF). Due to the complex shape of the structure, the individual vibration modes do not exhibit purely translational motions, but generally a coupled transversal, longitudinal and rotational motion. Thus individual Frequency Response Functions (FRF) have peaks corresponding to several modes. In one hand this enables to cross-check the measured frequencies but in the other hand closely spaced frequencies are difficult to identify.
The first few lower frequencies were identified (Table 1) and representative FRF curves are shown in Figs. 5 and 6. The continuous lines represent the average curves and the dashed lines are the limits of standard deviations.

Table 1. Natural frequencies and corresponding damping ratios.

Mode	*Frequency* [Hz]	*Direction*	*Damping* [%]
1	2.45	Longitudinal	1.05
2	2.70	Torsional	1.34
3	2.90	Transversal	1.05
4	3.35	Transversal	1.42
5	3.50	Longitudinal	1.88
6	4.25	Longitudinal	1.97
7	5.30	Longitudinal	2.21

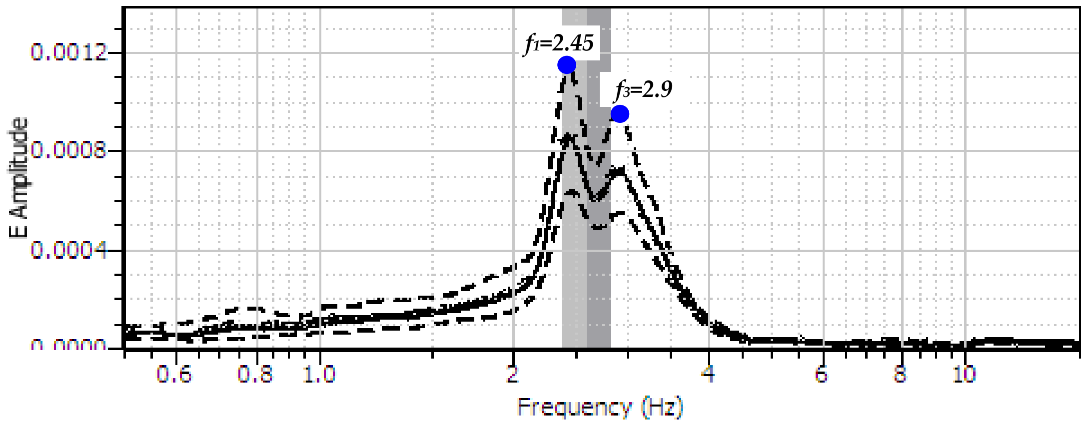

Figure 5. FRF curve recorded on point 2.

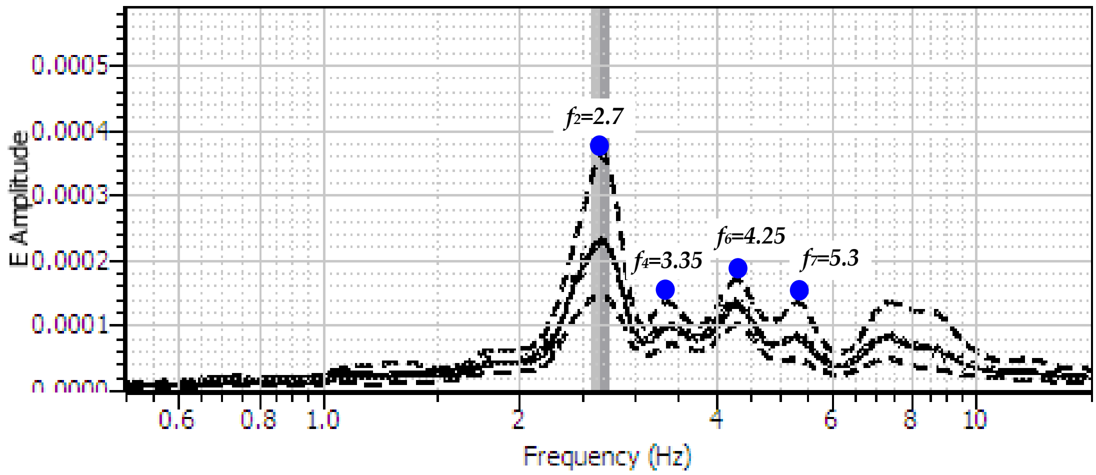

Figure 6. FRF curve recorded on point 5.

4 MODAL AND SEISMIC ANALYSES

In order to portrayed the elastic seismic behaviour of the building a three-dimensional analytical model was developed using SAP2000 [CSI 2004]. The model included the entire peripheral masonry wall system, the floor and roof diaphragms, and the steel framing (Fig. 7). A modal analysis was first carried out to validate the model. A minor adjustment of the elastic modulus of the masonry achieved reasonable correlation with the experimental results.

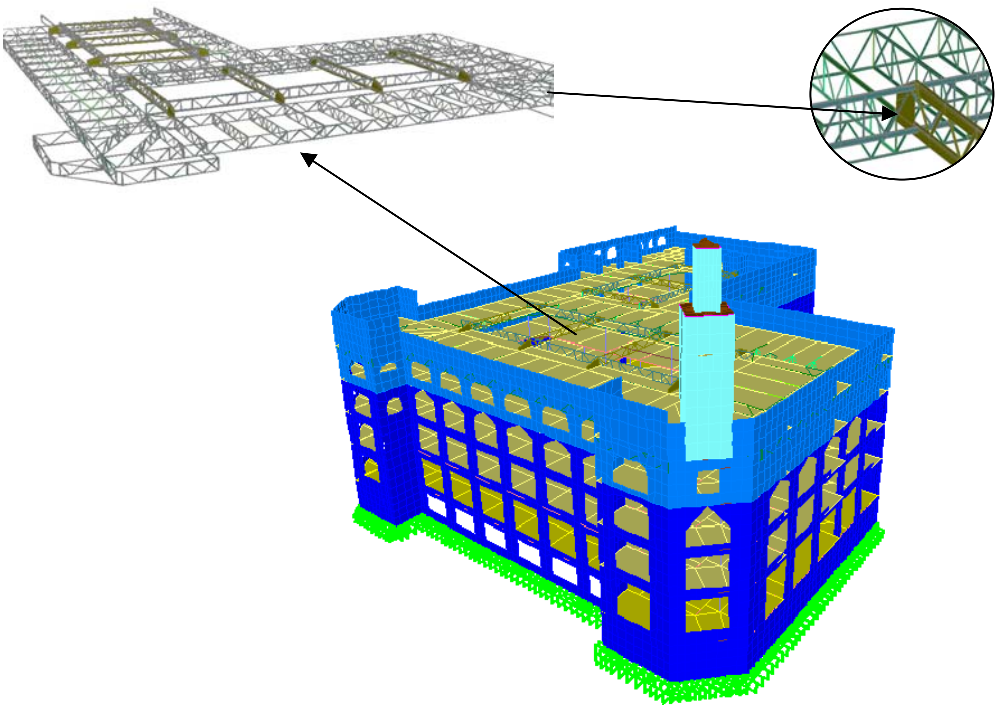

Figure 7. Three-dimensional analytical model.

A spectrum response analysis was performed by applying an acceleration spectra derived from the RPA99v2003 (Algerian seismic code). The seismic response of the building was studied in details to understand the vulnerability of each structural element particularly the masonry walls.
Figure 8 shows the stress distribution in the masonry walls where we can notice that the masonry around openings is subjected to substantially greater stress demand. On the basis of these results, several critical zones were identified for strengthening.

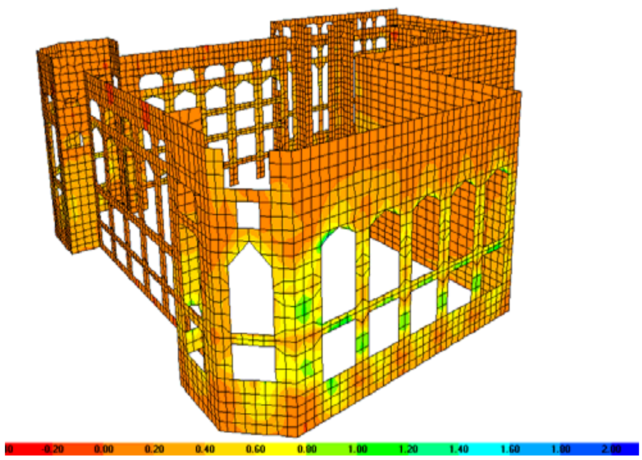

Figure 8. Stress distribution in the perimeter masonry walls.

5 STRUCTURAL STRENGTHENING

As outlined earlier, critical components are localised in the vicinity of the lower openings of the masonry walls. Considering the different strengthening schemes of masonry walls to enhance their in plane strength capacity, it was decided to use the technique based on the fibre-reinforced polymers which is most suitable in this case because of the high demand to capacity ratio. Fibre reinforced polymers (FRPs) can be adhered to the surface of a masonry wall with epoxy to provide strength across potentially weak planes. Because of the high tensile strength of FRP materials, a fairly thin sheet can provide substantial strength and confinement to the masonry. Though lateral strength of masonry wall can be enhanced several fold using FRP sheets, inelastic deformation capacity may be limited as a result of debonding of the sheets which occurs suddenly with little ductility. Thus, FRP materials should be placed strategically on those piers that are likely to attract damage first so that alternate, and more ductile, mechanisms can occur. The locations and directions of the FRP sheets are indicated on Figure 9 according to the results obtained from the dynamic analysis. In order to relieve the high stresses around the lower openings on the wall, a reinforced concrete rings are provided as shown on Figure 10.

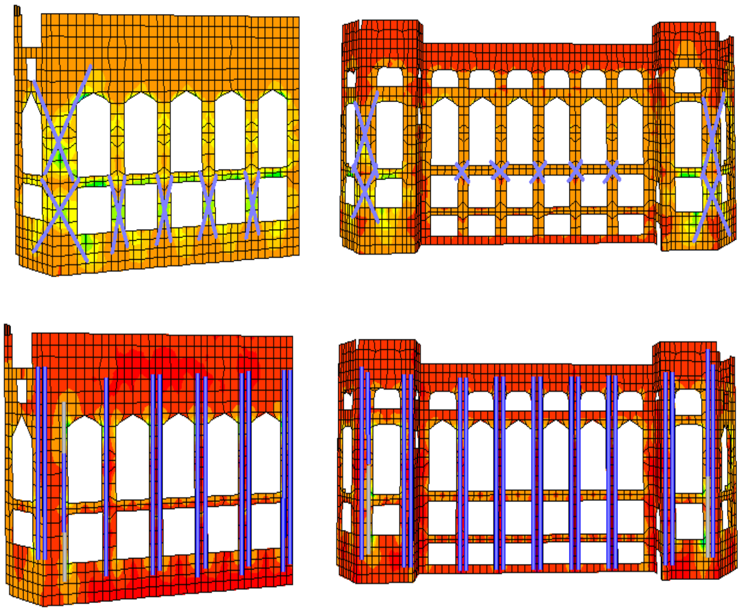

Figure 9. Fibre reinforced polymer locations.

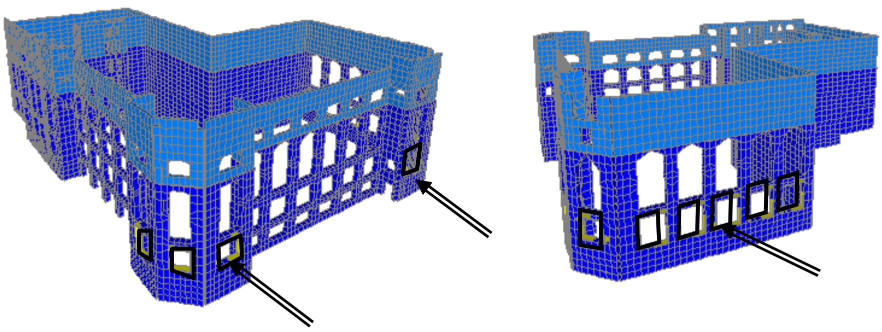

Figure 10. Reinforced concrete windows frames.

6 CONCLUSION

Ancient masonry bearing walls are reputed to be vulnerable to seismic loading. The old masonry becomes even weaker because of the effect of degrading agents which alter the strength and energy dissipation capacity that are distinctive characteristics to resist earthquakes. To rehabilitate such buildings, it is of paramount importance to evaluate their actual resistance capacity. In addition to conventional material testing, the use of ambient vibration testing is efficient to determine the overall dynamic characteristics of the building. Based on simple dynamic analysis it is possible to determine the critical or deficient zones. Strengthening techniques based on fibre reinforced polymers is appropriately used for the particular cases of high demand to capacity ratio that had been detected in many locations of the perimeter walls. In addition, the high stress concentration around the big openings was relieved by using reinforced concrete rings. The combined upgrading technique offers an acceptable stability and strength increase and preserves the architectural aspect of the building.

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