Structural Engineering and Mechanics, Vol. 40, No. 1 (2011) 1-11
DOI: http://dx.doi.org/10.12989/sem.2011.40.1.001

Ambient vibration tests on a 19 – story asymmetric steel building

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(Received April 24, 2010, Revised November 15, 2010, Accepted June 22, 2011)

Abstract. Ambient vibration tests were carried out to evaluate the dynamic properties of an asymmetric steel building with semi-rigid connections. The test case has many non-structural elements, constructed in the city of Tehran (Iran). The tests were conducted to obtain natural frequencies, mode shapes and damping ratio of the structure and then Fourier transform were used to analyze the velocity records obtained from the tests. The first and second natural periods of the building were obtained as 1.37 s and 1.28 s through the test and damping ratio for the first mode was calculated as 0.047. However, Natural periods obtained from finite element model have higher values from those gained from ambient vibration. Then the model was calibrated by modeling of the in-fill masonry panels at their exact locations and considering the boundary conditions by modeling two blocks near the block No. 3, but the differences were existed. These differences may be due to some hidden stiffness of nonstructural elements in the low range of elastic behavior, showing the structure stiffer than it is in reality.

Keywords: ambient vibration; dynamic characteristics; natural frequency; mode shape; steel building

1. Introduction

Dynamic characteristics of structures play an important role in predicting their behavior under the medium-strong earthquake ground motions occurring which have been observed in many parts of the world (Fu 2009). One of the applications of identifying dynamic characteristics is the investigation of health monitoring of structures, which has been actively investigated in the recent years (Chen *et al.* 2010).

These characteristics can be obtained through either mathematical models or experimental methods (Clotaire and Gueguen 2006). In the experimental methods, earthquake and ambient vibration records are used to identify dynamic characteristics of structures such as natural frequencies, mode shapes and damping ratios (Fragiacomo *et al.* 2004).

All structures are subject to many environmental excitations such as wind, traffic, human activities and so forth. One can record the structures response to these excitations by sensitive sensors. Ambient vibration study uses recorded data to predict the dynamic characteristics of structures, so

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this method is an economical way to achieve dynamic parameters, because it does not need any excitation instruments (Takhzod and Blondet 1997). Moreover, in countries with low seismic hazard, the methods, which are applicable for strong motion prone countries to evaluate seismic behavior, are not inadequate and financially unrealistic. Then ambient vibration tests are applied to identify the modal characteristics of such buildings (Clotaire *et al.* 2009). Also this method is the most efficient among the dynamic testing techniques, especially for large civil structures, where input excitation cannot be directly measured (Gul and Catbas 2008).

Skolnic *et al.* (2007) performed ambient vibration tests on Louis and Doris Factor Building, located at the UCLA campus. The building was instrumented by the USGS[1]. After the tests, the collected data were used to estimate the dynamic properties of the building and then a finite element model of the building was updated. The results showed that the combined use of modal system identification and model updating method can display the state of the existing structures.

Chen and Qu (2009) applied ambient vibration tests to identify the dynamic characteristics of Kao Ping Hsi cable-stayed bridge under traffic and environmental wind loads. The modal parameters obtained from the tests were compared with those used in the finite element analysis. The finite element model was refined by the experimental results and a comparison between the results of the test and the updated finite element model showed reasonable agreements for the first several modes in the two directions.

Beyen (2008) conducted ambient vibration tests on Fatih mosque (Istanbul, Turkey) after the Kocaeli earthquake (17th August 1999) to identify the dynamic characteristics of the structure. The ambient vibrations were recorded by single-component seismometers, which were placed at critical points. Then, dynamic characteristics of the structure were presented under both earthquake and ambient vibrations.

Bayraktar *et al.* (2008) applied ambient vibration tests on a Turkish style reinforcement concrete structure located in Trabzon. They modeled the structure using ANSYS finite element program, conducted modal testing, and finally updated the model. They could identify the natural frequencies, mode shapes and damping ratios of the structure, concluding that finite element model updating was effective on evaluation of the seismic behavior of the structure.

A structural health monitoring research was carried out by Khaldoon *et al.* (2008) on a historical monument in Jordan. Ambient vibration tests were applied to assess the modal characteristics of the structure, because the minaret had cultural value and touristic importance, so a non-destructive method had to be allowed for the experimental investigation. At the end, such dynamic parameters as natural frequencies and mode shapes were extracted. A 3-D finite element model of the minaret was also developed, and the analytical model was updated.

Ventura *et al.* (2003) applied ambient vibration tests on a base isolated apartment building in Takamatsu, Japan. The finite element model of the building and isolators was calibrated later. At the end, they specified the natural frequencies, mode shapes and damping ratio of the structure.

After Northridge earthquake (1994), two ambient vibration tests were conducted on a concrete building in Van Nuys, California by Ivanovic *et al.* (2000). Although they could calculate the frequencies and mode shapes of the building, locating of the damages by the recorded data was not possible.

In this research, a 19 story asymmetric steel building (Tehran, Iran) was considered as a test case.

[1]U.S. Geological Survey

Fig. 1 A view of the building façade

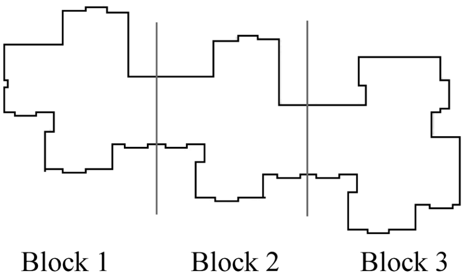

Fig. 2 Three Blocks of the building

The building consists of three blocks, separated with 21 cm seismic joints as shown in Figs. 1 and 2. Ambient vibration tests were performed on one of these blocks. A group of researchers conducted ambient vibration tests on the building and tried to determine the lateral and torsional natural frequencies, corresponding mode shapes and damping ratio. The dynamic characteristics identified here were compared with those obtained from the finite element model.

The building has been designed and constructed in 1973-1978 and has 3 basement stories underground and 16 stories above. The underground stories are used as parking and the rest (16 stories) have governmental land use. Each floor has 1949 m^2 area and 3.2 m height. The building does not have any specified lateral resisting system but some in-fill masonry panels.

In the building, the columns and the E-W beams have been constructed by INP profiles, reinforced by plates, and the N-S beams are CNP profiles. Semi-rigid and pin connections are used in the E-W and N-S directions, respectively. Additionally, the ceiling system is joist blocks.

There are retaining walls at all the three underground stories and their thicknesses are 40 cm for the heights less than 6.2 m and 30 cm for the heights higher than 6.2 m.

This study focuses on the block No. 3 and the ambient vibration tests were carried out to achieve the dynamic characteristics of the structure. Some of the first lateral frequencies, corresponding mode shapes and damping ratio were obtained in this research.

2. Instruments

CMG-6TD broad band sensor was used to record the ambient vibration of the building. This instrument is an ultra-lightweight digital three-axis seismometer consisting of three sensors in a sealed case, which can measure the north-south, east-west and vertical components of ground motion simultaneously (Fig. 3).

It includes internal flash memory storage for digital data and can be used either as a self-contained recording station or in conjunction with data acquisition software as a complete, high

Fig. 3 CMG-6TD

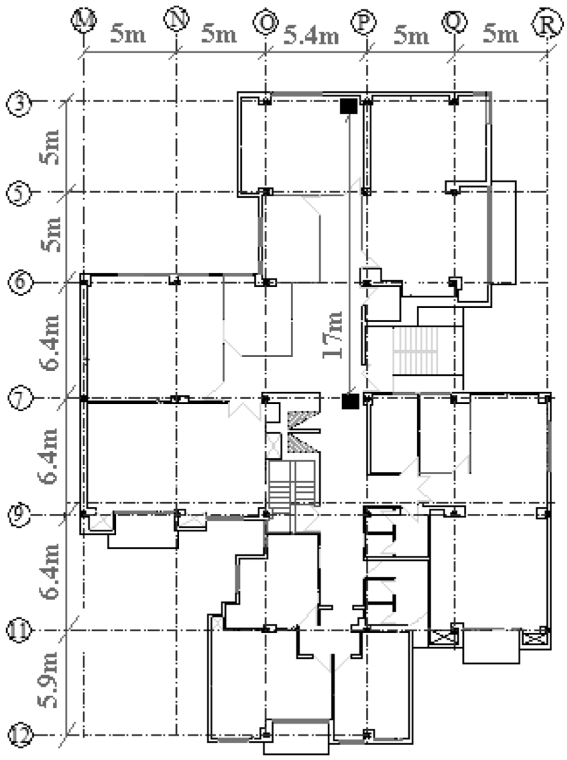

Fig. 4 Position of the sensors

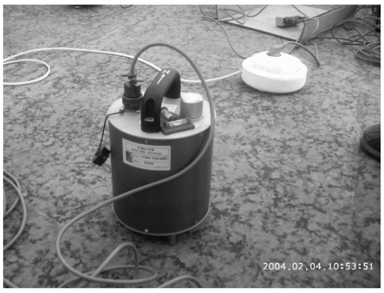

Fig. 5 One of the sensors at the roof of the building

Fig. 6 One of the sensors at the second floor of the building

quality seismic data recording system suitable for a wide range of local, regional or teleseismic studies.

Each seismometer is delivered with a detailed calibration sheet showing its serial number, measured frequency response in both the long period and short period sections of the seismic spectrum and sensor's DC calibration levels.

A set of ten sensors were used to record the structural responses. Two sensors were mounted at each of the -3, 2, 7, 12 and 16 stories (Fig. 4), one at the mass center and another at the edge of the structure. The data were recorded during 20 min and the sample rate was 100 samples per second.

Figs. 5 and 6 show the sensors at the roof and second floor of the building respectively.

3. Data processing

The recorded velocity time-histories were analyzed by MATLAB software to obtain Fourier amplitude spectra of the floors. A set of responses, with 20 min intervals, were selected and divided into one minute interval responses. Consequently, each data channel contained almost 6000 samples.

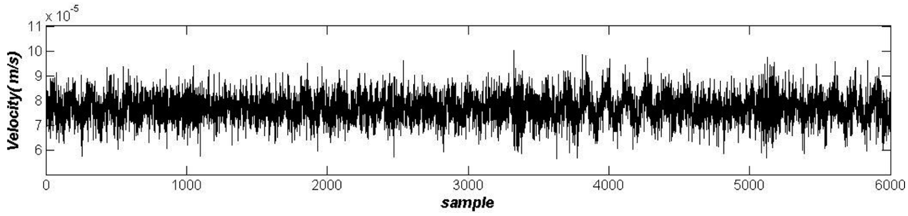

Fig. 7 One of the records of the building at the mass center of second floor

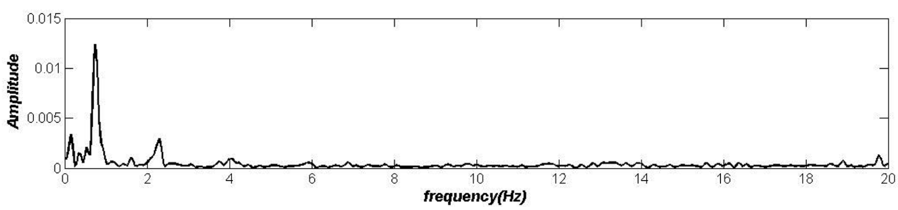

Fig. 8 One of the Fourier amplitude spectra corresponding to a record at the roof of the building

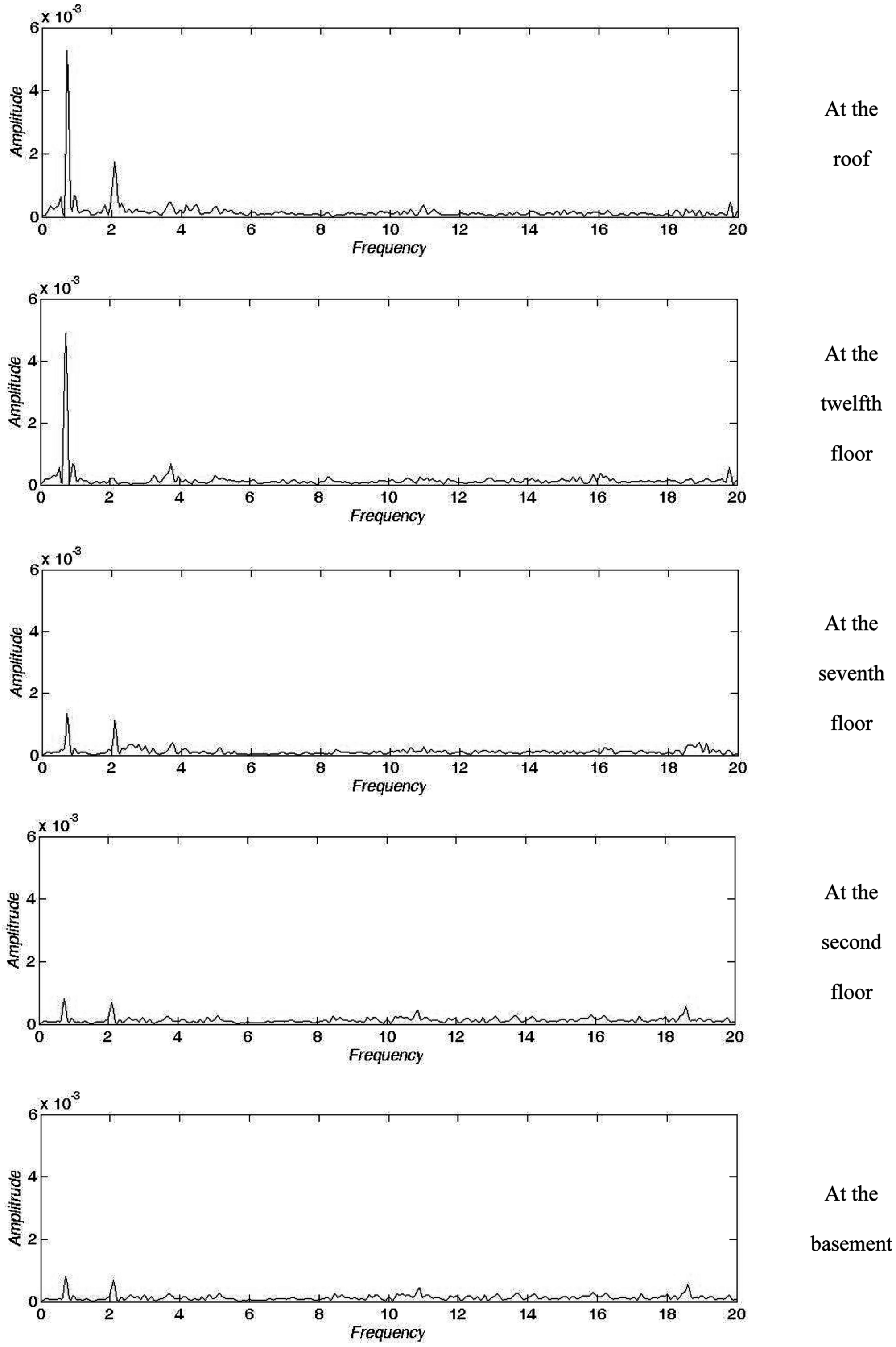

Fig. 9 Translational Fourier amplitude spectra at various floors of the building

A sample of the records of the building is shown in Fig. 7.

All records were filtered by wavelet filter before processing. It has been shown in the previous researches that wavelets can remove noise more effectively than the preceding used methods (Mallat 2009). So in the present study, wavelet transform was used to denoise the data. This was accomplished by applying a discrete wavelet transform, using "sym8" mother wavelet to the original data and considering the Heursure threshold selection method and soft thresholding rule. The resulting coefficients below some value in magnitude were eliminated. Then inverse transform was applied to obtain a smoother version of the original data (Donoho and Johnstone 1994).

By summing the Fourier amplitudes obtained from two sensors on each floor, Fourier amplitude spectrum of translational vibration was gained and that of torsional vibration was obtained by subtracting two Fourier amplitudes on each floor and then dividing the obtained result by the distance between the two sensors (Takhzod and Blondet 1997). Fig. 8 shows one of the Fourier amplitude spectra of the building.

Natural vibration frequencies were detected by identifying the significant peaks at Fourier amplitude spectra. Phase angles were obtained from the phase spectrum. Phase angles specify if the floors move in the same directions or not. A phase angle close to 0 radian shows that the floors move at the same directions and a phase angle close to π radians indicates that the floors move in the opposite directions.

The corresponding mode shape was obtained by normalizing the Fourier amplitudes (measured at the amplitude corresponding to the natural period) to a unit value on the level 16.

This method was applied to estimate the vibration frequencies and mode shapes of the building. For example, Fourier amplitude spectra at the different floors of building, which are obtained from the simultaneously recorded data, are shown in Fig. 9.

Damping ratio is obtained based on the half power band width technique. In this method, the Fourier amplitude at the peak frequency (f_n) is divided by $\sqrt{2}$ and the two corresponding frequencies are obtained from the Fourier amplitude spectra (f_1, f_2).

Then the damping ratio is calculated by $\xi = ((f_1 - f_2)/2f_n)$ (Chopra 1998). In this study, damping ratio was obtained as 0.047 for the first lateral mode.

4. Finite element model

The SAP 2000 software was used to model the building analytically. Such assumptions as linearization and rigid diaphragm were included in the model. Finite element model of building is shown in Fig. 10.

Beams and columns were modeled by frame elements. Material properties used for beams and columns sections are according to Table 1. It is noticeable that these properties were determined using several tests.

As mentioned before, semi-rigid connections have been used in the E-W direction.

We used developed software to model their moment-rotation behavior (Shakib *et al.* 2008).

The retaining walls and masonry in-fill panels were modeled by crosswise and diagonal elements, respectively. The elastic in-plane stiffness of an in-fill panel prior to cracking shall be represented with an equivalent diagonal element of determined width and the equivalent strut shall have the same thickness and modules of elasticity as the in-fill panel represents (FEMA 356).

Those masonry in-fill panels, which have openings, were modeled by reduced stiffness diagonal

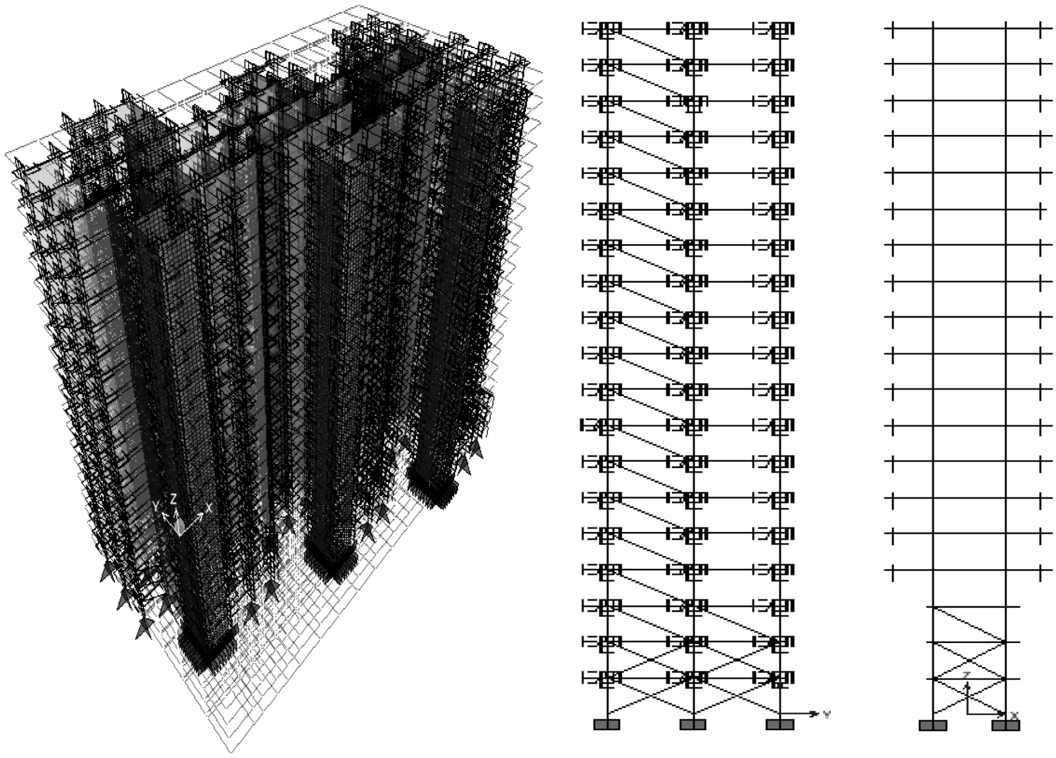

Fig. 10 Finite Element model of the building

Table 1 Materials' properties used in the finite element model

Steel	Modules of Elasticity = 200 Gpa	F_y = 250 Mpa	F_u = 407.7 Mpa
Concrete	Modules of Elasticity = 26.5 Gpa	f_c' = 28.1 Mpa	

elements (Asteris 2003).

Two other blocks were also modeled to create real situation. At the end, the model was analyzed and the period of the first mode was obtained approximately as 4.5 s and this period indicates that the building has high flexibility.

Supplementary studies on lateral resistance of building were done (Shakib *et al.* 2008) and after nonlinear analysis, it was concluded that the building can not resist against lateral load and should be rehabilitated.

After rehabilitation of the building, structure was modeled again and period of the first mode was obtained 2.1 seconds.

5. Results

The natural periods, which were obtained from ambient vibration tests, are displayed in Table 2.

After the tests, finite element model was calibrated by modeling all of the in-fill panels and

Table 2 Natural periods obtained from ambient vibration tests

Mode number	1	2	3	4	5
Period (s)	1.37	1.28	0.7	0.48	0.44

Table 3 Natural periods obtained from finite element model

Mode number	1	2	3	4	5
Period(s)	2.1	1.5	1.3	0.75	0.5

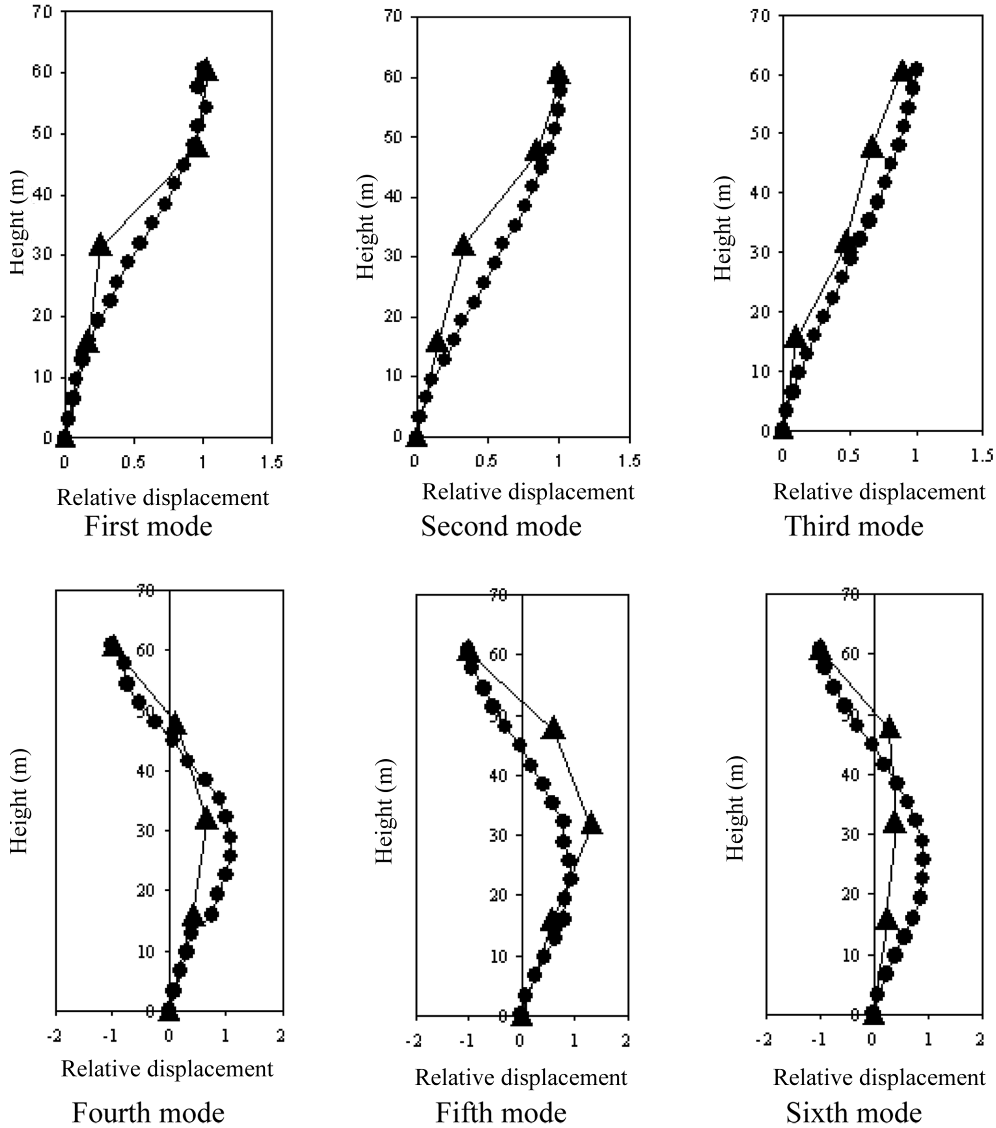

Fig. 11 Mode shapes obtained from finite element model and ambient vibration tests (▲: Tests results, ✹: Model results)

applying the boundary conditions via modeling of two blocks near the main block. After analyzing the model, the period of the first mode was obtained different from that of the tests results. The natural periods, which were obtained from the finite element model of the resistant structure, are shown in Table 3.

The corresponding mode shapes are also presented in Fig. 11.

6. Conclusions

A method for identifying the dynamic characteristics of a structure was investigated.

After the ambient vibration tests, the recorded velocity time-histories were analyzed by MATLAB software to obtain Fourier amplitude spectra of them. As mentioned before, the period of the first mode, obtained from ambient vibration tests was equal to 1.37 s. On the other hand, the first period of the structure, obtained from finite element model had a high value. It is worth noting that the structure does not have any lateral resistant system and this high value of the first mode gained from finite element model shows that the structure has large flexibility.

Then the model was calibrated by modeling of the in-fill masonry panels at their exact locations and considering the boundary conditions by modeling two blocks near the block No. 3. But the differences were existed. The differences may be due to extra nonstructural elements showing the structure stiffer than it is in reality.

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