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Construction stage effect on the dynamic characteristics of RC frame using operational modal analysis

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Abstract. In this study, dynamic characteristics such as natural frequencies, mode shapes and damping ratios of RC frame is determined for different construction stages using Operational Modal Analyses method under ambient vibration. Full scaled, one bay and one story RC frames are selected as an application for different construction stages such as plane, brick in-filled and brick in-filled with plaster. The RC frame is vibrated by natural excitations with small impact effects and the response signals are measured using sensitive accelerometers during ambient vibration tests. Measurement time-frequency span and effective mode number are determined by considering similar studies in literature. Sensitive seismic accelerometers are used to collect signals obtained from the experimental tests. To obtain experimental dynamic characteristics, output-only system identification technique is employed namely; Enhanced Frequency Domain Decomposition technique in the frequency domain. It is demonstrated that the ambient vibration measurements are enough to identify the most significant modes of RC frames.

Keywords: ambient vibration; dynamic characteristics; enhanced frequency domain decomposition; operational modal analysis; RC frames

1. Introduction

RC frame systems are one of the most popular structural systems used for construction of reinforced concrete short buildings. On the other hand, RC frames are in-filled to constitute different living space in the same environment using various structural materials such as brick, aerated concrete blocks and panels. For structural analysis, usually contribution of infill walls is ignored. However, experimental and theoretical studies show that infill walls increase considerably stiffness, energy dissipation and load carrying capacity of RC frames. There are many studies have been carried out on infill walls (Klingner and Bertero 1978, Govindan *et al*. 1986, Maharani 1996, Sahoo and Rai 2010, Özsayın *et al*. 2011). On the other hand Turkish Seismic Code (2009) and FEMA 356 (2000) mention detailed on this subject. Although there are many studies on RC frame, knowledge about effects of infill walls on dynamic behaviors are limited.

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Dynamic behavior of structures depends on dynamic characteristics of structures such as natural frequencies, mode shapes and modal damping ratios. The dynamic characteristics are determined analytical and experimentally according to the structural properties, material properties, boundary conditions and damage cases of the structure. Analytical dynamic characteristics are usually determined during project stage. In this method, finite element model of structure are constituted using proper material properties and boundary conditions.

Finally, natural frequencies and mode shapes are obtained after implementing free vibration analysis. However, many researchers have emphasized these results don’t reflect the actual characteristics of current structure (Morin *et al*. 2002, Reynolds *et al*. 2002, Sasaki *et al*. 2004, Law *et al*. 2006). Therefore, experimental methods are needed to verify accuracy of analytically determined dynamic characteristics and calculate earthquake forces structure is subjected. Experimental methods are directly applied on the structures and current dynamic behaviors are obtained. There are many studies are available in technical literature on experimental methods (Bayraktar *et al*. 2006, Bayraktar *et al*. 2009, Bayraktar *et al*. 2010). Modal tests were used initially advanced mechanical and aerospace engineering disciplines (Ewins 1984, Juang 1994, Maia and Silva 1997). After adopting the test method to civil engineering problems, Tests have been carried out on different structures such as bridges (Zivanovic *et al*. 2006, Bayraktar *et al*. 2007, Günaydın *et al*. 2012), dams (Zhou *et al*. 2000, Wang and Li 2007), buildings and other structures.

Today, experimental measurement methods are commonly used to determine dynamic characteristics of structures. There are basically two different experimental measurement methods; Ambient Vibration Test-AVT (Operational Modal Analysis-OMA), and Forced Vibration Test-FVT (Experimental Modal Analysis-EMA). In the forced vibration test, structure vibrated by a known input force such as impulse hummers, drop weights and electrodynamics shakers. In the ambient vibration test, only the response is measured using environmental excitation such as wind, human walking or traffic. Afterwards modal parameters are extracted from the measured responses using a wide variety of methods (Sevim *et al*. 2010).

It is known that dynamic characteristics change depending on construction stages of buildings. Mechanical properties of concrete for each floor are possibly different in RC buildings. In addition, estimation of dynamic characteristics of buildings is going to be more difficult, when infill walls and plaster cover are considered. For these reasons, it is very important to determine dynamic characteristics using modal test by taking into account current situation of buildings.

Under the circumstance, in this paper constituting part of an ongoing experimental and theoretical study, dynamic characteristics such as natural frequencies, mode shapes and modal damping ratios of a full scaled, one bay and one story brick in-filled RC frame were determined for different construction stages (plane, brick in-filled and brick in-filled with plaster) using OMA under ambient vibration.

2. Formulation

In OMA, the structure is excited by unknown input force and responses of the structure are measured. On the other hand in EMA, the structure is vibrated using known inputs as impact hammer or shaker. Some heavy forced excitations become very expensive and sometimes may cause damage to the structure. However, ambient vibrations such as traffic, waves, winds, and their combination are environmental excitations. The main advantages of ambient vibration test are: a) testing is cheap and fast, since the equipment for excitation is unnecessary; b) testing does not interfere with the operation of the structure; c) the measured response represents for the real operating conditions of the structure. Therefore, the system identification techniques through ambient vibration measurements have become very attractive (Altunışık *et al*. 2011).

In OMA method, ambient excitation does not lend itself to Frequency Response Function (FRFs) or Impulse Response Function (IRFs) calculations because the input force is not measured in an ambient vibration test. Therefore, a modal identification procedure will need to base itself on output-only data (Ren *et al*. 2004). In OMA method, there are several modal parameter identification techniques available such as Peak Picking (PP), Enhanced Frequency Domain Decomposition (EFDD), Stochastic Subspace Identification (SSI), etc. In this study, Enhanced Frequency Domain Decomposition (EFDD) technique is used to extract dynamic characteristics of the RC frame (Sevim *et al*. 2010).

EFDD technique is an extension to FDD technique. In the technique, modes are simply picked locating the peaks in Singular Value Decomposition plots (SVD) calculated from the spectral density spectra of the responses. As FDD technique is based on using a single frequency line from the Fast Fourier Transform analysis (FFT), the accuracy of the estimated natural frequency depends on the FFT resolution and no modal damping is calculated. Compared to FDD, EFDD gives an improved estimate of both the natural frequencies and the mode shapes and also includes damping (Sevim *et al*. 2010).

In EFDD, the SDOF Power Spectral Density function, identified around a peak of resonance, is taken back to the time domain using the Inverse Discrete Fourier Transform (IDFT). The natural frequency is obtained by determining the number of zero-crossing as a function of time, and the damping by the logarithmic decrement of the corresponding SDOF normalized auto correlation function. The SDOF function is estimated using the shape determined by the previous FDD peak picking-the latter being used as a reference vector in a correlation analysis based on the Modal Assurance Criterion (MAC). A MAC value is computed between the reference FDD vector and a singular vector for each particular frequency line. If the MAC value of this vector is above a user-specified MAC rejection level, the corresponding singular value is included in the description of the SDOF function. For example, the number of singular values included in the identification of the SDOF function will be larger for the lower MAC rejection levels. In FDD technique, the relationship between the unknown input and the measured responses has the expression (Felber 1993, Peeters 2000, Bendat and Piersol 2004).

$$[G_{yy}(j\omega)] = [H(j\omega)]^{*}[G_{xx}(j\omega)][H(j\omega)]^{T} \quad (1)$$

Where $G_{yy}(j\omega)$ r Power Spectral Density (PSD) matrix of the input, r is the number of inputs, $G_{yy}(j\omega)$ is the mxm PSD matrix of the responses, m is the number of responses, $H(j\omega)$ is the mxr Frequency Response Function (FRF) matrix, and * and superscript T denote complex conjugate

Table 1 Mixture proportions of the concrete

Mixture proportions	Quantities of aggregates (kg/m^3)					Saturation water (kg/m^3)	Mixing water (kg/m^3)	Cement (kg/m^3)
	Sieve Size (mm)							
	0.5-1.0	1.0-2.0	2.0-4.0	4.0-8.0	8.0-16.0			
	265.50	265.50	265.50	442.50	531.00	7.080	185	370

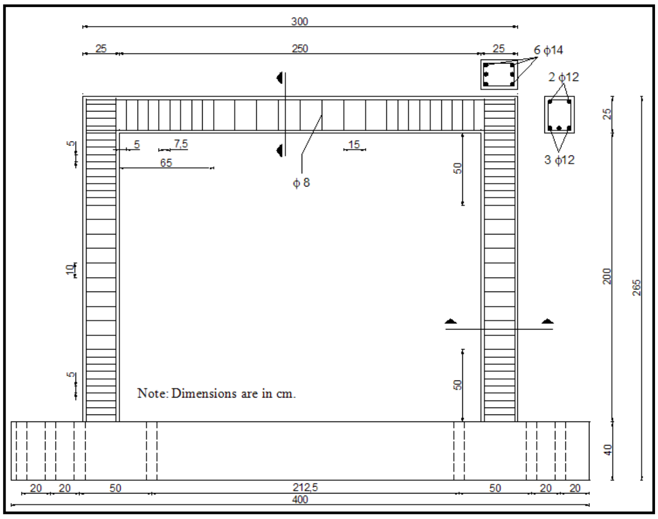

Fig. 1 Dimensions and reinforcement details of the RC frame

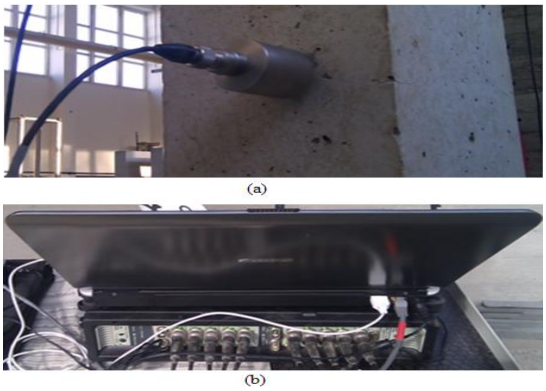

Fig. 2 Accelerometers and data acquisition system used for OMA

and transpose, respectively. Solution of the Eq. (1) is available in detail in the literature (Brincker *et al*. 2000).

To estimate modal damping ratios, the singular values near the peak with corresponding singular vector having modal assurance criteria (MAC) higher than a MAC rejection level are transferred back to time domain through inverse Fast Fourier transform (FFT), which is an approximated correlation function of the equivalent single degrees of freedom (SDOF) system. From the free decay function of the SDOF system, the damping ratio can be calculated by the logarithmic decrement technique.

3. Descriptions of RC frames

As mentioned previously, in this study, dynamic characteristics such as natural frequencies, mode shapes and modal damping ratios of a full scaled, one bay and one story brick in-filled RC frame were determined for different construction stages (plane, brick in-filled and brick in-filled with plaster) using Operational Modal Analyses (OMA) under ambient vibration. Dimensions and reinforcement details of the RC frame are given in Fig. 1. RC frame was fixed to the rigid floor from base.

Mixture proportions of the concrete used in producing frame is given in Table 1. CEM II/B-M (P-LL) 32.5 R was used as cement and dosage was kept constant at 370 kg/m^3 with 0.5 W/C ratios. Characteristic compressive strength and elasticity modulus of the concrete is 25.14 MPa and 28670 MPa, respectively.

Fig. 3 A scene from ambient vibration tests of plane frame

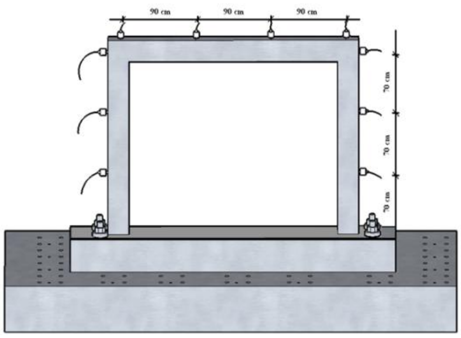

Fig. 4 Schematic views of accelerometer locations

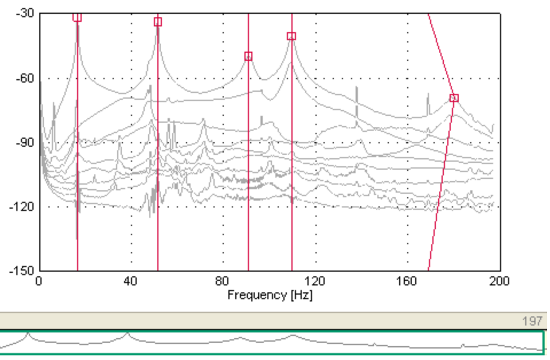

Fig. 5 SVSDM and AASD of the data set for plane frame

4. Operational modal analyses (Ambient vibration test) and modal identification

Ambient vibration tests were conducted on RC frame to determine its natural frequencies, mode shapes, and damping ratios. Measurements were implemented for plane, brick in-filled and in-filled with plaster. Measurements were taken from columns and beam. Tests were carried out using B&K8340 type uni-axial accelerometers. These accelerometers have 1000 m V/g sensitivity and 0.1-6000 Hz frequency span. During the tests, frequency span was selected as 0.1–300 Hz according to the initial finite element results. The measurements were performed for 15min and excitations were provided from small impact effects. Accelerometers were placed horizontally and vertical to columns and beam, respectively. In the ambient vibration tests, B&K 3560 data acquisition system with 17 channels was used. Signals obtained from the tests were recorded and processed by OMA software (2006). The dynamic characteristics of frame for different construction stage were extracted by EFDD technique. Accelerometers and data acquisition system used for OMA are shown Fig. 2.

5. Results and discussion

5.1 Plane frame measurements

Ambient vibration tests for plane frame have been conducted for 15 minutes since amplitude of force and its change in time are unknown. Totally from ten points measurements were taken on plane frame with accelerometers (three for each column and four for beam). To identify the mode shapes and natural frequencies of frame more correctly ten accelerometers are located on frame in the vertical and lateral directions (three for each column and four for beam). A scene from ambient vibration tests for plane frame and schematic view of accelerometer locations are given in Fig. 3 and Fig. 4, respectively.

Singular values of spectral density matrices (SVSDM) and average of auto spectral densities (AASD) of the data set obtained from EFDD technique are shown in Fig. 5. In this figure, peak values are vibration resonances of the frame and frequency value for each resonance shows natural

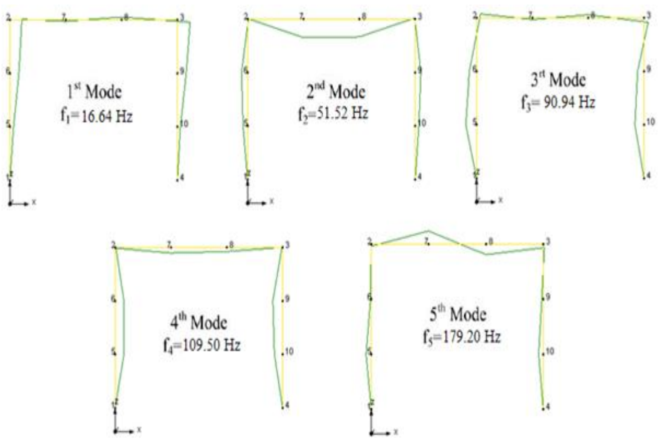

Fig. 6 The first five modes shapes of plane frame

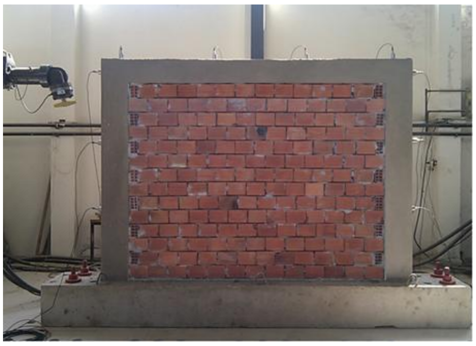

Fig. 7 A scene from ambient vibration tests of brick in-filled frame

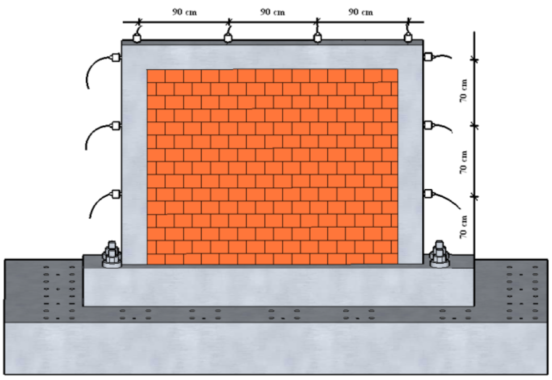

Fig. 8 Schematic views of accelerometer locations

Table 2 Mixture proportions of the concrete

Modes	Natural frequencies (Hz)	Modal damping ratios %
1	16.64	1.093
2	51.42	0.612
3	90.94	1.936
4	109.50	0.911
5	179.20	2.190

frequencies. As seen in Fig. 5, five natural frequencies are obtained clearly between 16-180Hz frequency span. Modal damping ratios are obtained by using these frequencies at peak values.

The first five mode shapes of plane frame are seen Fig. 6 and natural frequencies and modal damping ratios obtained from the tests are given in Table 2.

5.2 Brick in-filled frame measurements

Ambient vibration tests have been carried out on brick in-filled RC frame to determine effects of construction stages on dynamic characteristics, as well. As infill materials, brick having 13.5 x 19 x 19 cm dimensions were used. Average compressive strength and elasticity modulus of brick are 5.2 MPa and 4000 MPa, respectively. Compressive strength of mortar used in in-filled wall is 4.52 MPa.Measurements were taken at the same points of frame. A scene from ambient vibration tests of brick in-filled frame and schematic view of accelerometer locations are given in Figs. 7 and 8, respectively.

Singular values of spectral density matrices (SVSDM) and average of auto spectral densities (AASD) of the data set obtained from EFDD technique are shown in Fig. 9. As seen in the figure, five natural frequencies are obtained clearly between 63-227 Hz frequency span.

The first five mode shapes of brick in-filled frame are seen Fig. 10 and natural frequencies and modal damping ratios obtained from the tests are given in Table 3. These results show that in-fill walls increase reasonably frequencies and stiffness of RC frame. Mode shapes of the frame are different compared to plane frame except for first mode.

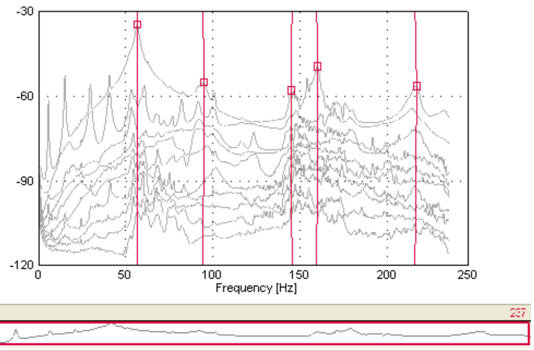

Fig. 9 SVSDM and AASD of the data set for brick in-filled frame

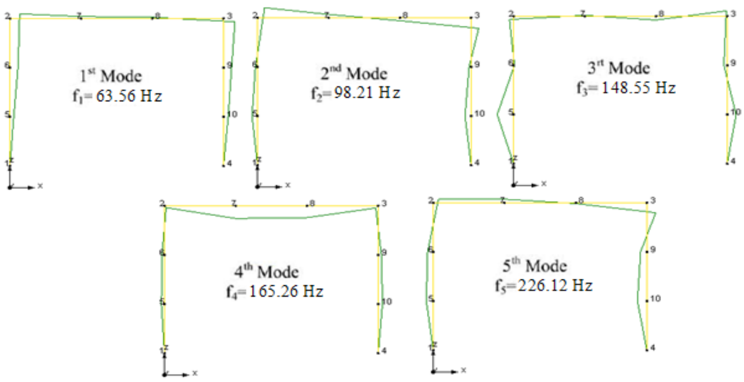

Fig. 10 The first five modes shapes of plane frame

Fig. 11 A scene from ambient vibration tests of brick in-filled with plaster frame

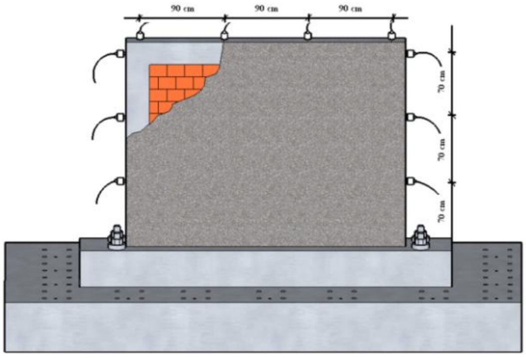

Fig. 12 The first five mode shapes of brick in-filled frame

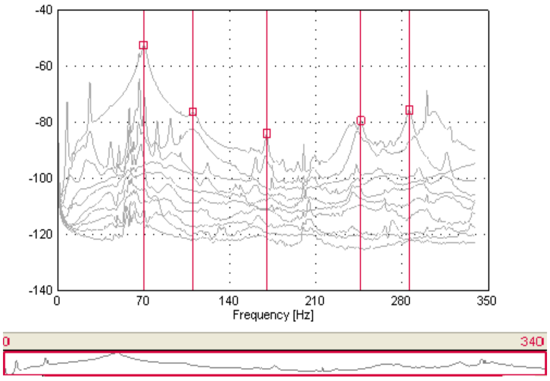

Fig. 13 SVSDM and AASD of the data set for brick in-filled with plaster frame

Table 3 Natural frequencies and damping ratios of brick in-filled frame

Modes	Natural frequencies (Hz)	Modal damping ratios %
1	63.56	1.822
2	98.21	1.613
3	148.55	0.826
4	165.26	0.786
5	226.12	0.812

5.3 Brick In-filled with paster frame measurements

Finally, OMA with ambient vibrations have been carried out on brick in-filled with plaster RC frame to determine effects of construction stages on dynamic characteristics. Measurements were taken at the same points of frame. Compressive strength of mortar used for plaster is 2.56 MPa. A scene from ambient vibration tests of brick in-filled with plaster RC frame are seen in Fig. 11 and schematic view of accelerometer locations are given in Fig. 12.

Singular values of spectral density matrices (SVSDM) and average of auto spectral densities (AASD) of the data set obtained from EFDD technique are shown in Fig. 13. It is seen from Fig. 13, five natural frequencies are obtained clearly between 70-286 Hz frequency span.

The first five mode shapes of brick in-filled with plaster frame are seen Fig. 14 and natural

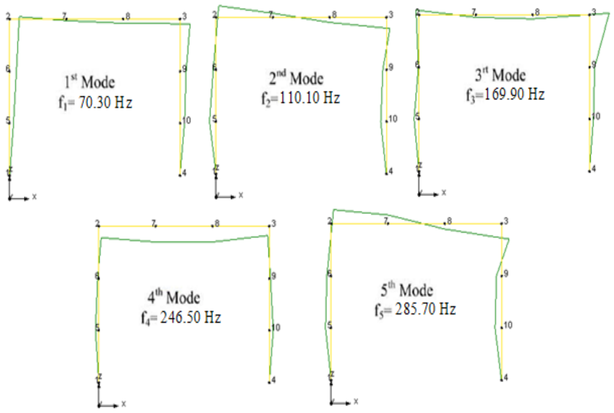

Fig. 14 The first five mode shapes of brick in-filled with plaster frame

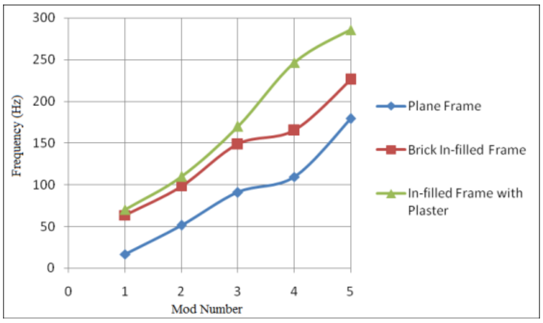

Fig. 15 Changing of the natural frequencies during construction stages

Table 4 Natural frequencies and damping ratios of brick in-filled with plaster frame

Modes	Natural frequencies (Hz)	Modal damping ratios %
1	70.30	2.091
2	110.10	1.810
3	169.90	0.513
4	246.50	0.460
5	285.70	0.725

frequencies and modal damping ratios obtained from the tests are given in Table 4.

These results show that small changes on frame such as plaster cover can cause different behavior, even if they are not taken into account for analysis. Changing of the natural frequencies during construction stages are given in Fig. 15.

6. Conclusions

In this paper, dynamic characteristics such as natural frequencies, mode shapes and modal damping ratios of RC frames for different construction stages (plane, brick in-filled and brick in-filled with plaster) were determined using OMA under ambient vibration. Based on the results of this investigation, the following conclusions can be made

• From the ambient vibration tests of the RC frames, a total of 5 natural frequencies were attained experimentally, which range between 16-286Hz. Considering the first five mode shapes, these modes can be classified into bending and lateral modes.

• The first fifth natural frequencies are obtained between 16-180Hz, 63-227 Hz and 70-286 Hz for plane, brick in-filled and in-filled with plaster conditions, respectively.

• In-fill wall and plaster increase considerably frequencies and stiffness, also change mode shapes. Thus, dynamic behavior of plane frame is quite different from in-filled frame.

• There is a good agreement between mode shapes obtained from brick in-filled and in-filled with plaster conditions. However some differences are seen in plane frame condition.

• The determination of natural frequencies of RC frames is the most important part of this study. Therefore, similar studies must be performed for other types of structures or structural elements.

• The damping ratios are obtained between 0.61-2.19%, 0.79-1.82%, 0.51-2.09% for plane, brick in-filled and in-filled with plaster using EFDD technique, respectively.

Consequently, in-filled walls change dynamic behavior of RC frame. This result shows that effects of in-fill walls should be considered for structural analysis. Otherwise, structures may be affected adversely by earthquake. Since, dimensions are determined using loads for ductility level of structures. Ignoring effects of in-fill walls do not necessarily means that we stay on the safe side for every time. In addition, it is shown the OMA is very important for obtaining current situation of structures for constitute more correct numerical models. Finally, it can be inferred from this study, behavior of structures quietly chances for different construction stages.

After the finite element model of the RC frame is constituted and dynamic characteristics are determined analytically, experimentally identified dynamic characteristics can be used as a reference and finite element model of the RC frame can be updated by using uncertain parameters such as material properties, boundary conditions and section areas.

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