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Modal parameter identification of in-filled RC frames with low strength concrete using ambient vibration

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Abstract. In this study, modal parameters such as natural frequencies, mode shapes and damping ratios of RC frames with low strength are determined for different construction stages using ambient vibration test. For this purpose full scaled, one bay and one story RC frames are produced and tested for plane, brick in-filled and brick in-filled with plaster conditions. Measurement time, frequency span and effective mode number are determined by considering similar studies and literature. To obtain experimental dynamic characteristics, Enhanced Frequency Domain Decomposition and Stochastic Subspace Identification techniques are used together. It is shown that the ambient vibration measurements are enough to identify the most significant modes of RC frames. The results indicate that modal parameters change significantly depending on the construction stages. In addition, Infill walls increase stiffness and change the mode shapes of the RC 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, like expected. Dynamic characteristics should be verified using finite element analysis. Finally, inconsistency between experimental and analytical dynamic characteristics should be minimize by finite element model updating using some uncertain parameters such as material properties, boundary condition and section properties to reflect the current behavior of the RC frames.

Keywords: ambient vibration; dynamic characteristics; efdd; ssi; operational modal analysis; rc frames; low strength concrete

1. Introduction

RC frames which find wide application in multistory buildings, are often infilled with brick or concrete-block masonry for functional reasons. In-filled frames, like other structures, should be designed to withstand lateral forces resulting from earthquake (Smith 1962, Klingner and Bertero 1978, Mehrabi *et al*. 1996, FEMA 356 2000, Sahoo and Rai 2010). The precision of the estimated forces induced by an earthquake used for analysis depend on dynamic characteristics of structures such as natural frequencies, mode shapes and damping ratio. The dynamic characteristics are significantly influenced by infill walls. Equations in design codes, do not properly account for the effects of infill walls. Furthermore, errors greater than ±50% were observed (Ellis 1980) when the

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natural frequencies, computed using empirical formulas were compared with measured natural frequencies. Hence, the dynamic characteristics of an in-filled frame should be determined by accounting for the effect of infill walls. Common misconception is that infill walls only increase the overall lateral load carrying capacity of frames, therefore, always contribute to seismic performance. However, several structural damages have occurred due to the presence of infilled walls during earthquake. In order to effectively reduce the damages caused by seismic activity, the dynamic characteristics of buildings must be well understood (Kodur *et al*. 1995).

The dynamic characteristics can be determined analytical and experimentally according to the structural and material properties, boundary conditions and damage cases of the structure. As mentioned earlier, analytical dynamic characteristics don't reflect the actual characteristics of current structure (Sun and Philip 1997, Reynolds *et al*. 2002, Law *et al*. 2006). Therefore, experimental methods are needed to verify accuracy of analytically determined dynamic characteristics and calculate earthquake forces. There are many studies are available in technical literature on experimental methods (Ewims 1984, Maia and Silva 1997, Ren *et al*. 2004, Dooms *et al*. 2006, Bayraktar *et al*. 2006, Zivanovic *et al*. 2006, Zivanovic *et al*. 2007, Brencich and Sabia 2008, Bayraktar *et al*. 2009, Bayraktar *et al*. 2010a, Bayraktar *et al*. 2010b).

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*. 2010a).

A review of the literature on behavior of in-filled frames (Kodur 1994) indicated that addition of infill walls can cause significant changes in the dynamic characteristics of buildings and influence their behavior during earthquakes. In addition, mechanical properties of concrete used for analysis may be different from cast-in-place RC buildings. For these reasons, it is very important to determine dynamic characteristics using modal test by taking into account current situation of buildings for structural analysis to achieve more consistent results.

Consequently, in this paper 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 frames with low strength concrete were determined for different construction stages (plane, brick in-filled and brick in-filled with plaster) using OMA under ambient vibration.

2. Formulation of operational modal analysis techniques

Ambient excitation does not lend itself to Frequency Response Functions (FRFs) or Impulse Response Functions calculations, since the input force is not measured in ambient vibration tests. Therefore, a modal identification method is required to base itself on output-only data (Ren 2004). There are several modal parameter identification techniques. In this study, EFDD and SSI techniques were used to extract dynamic characteristics of RC frames with low strength concrete.

2.1 Enhanced frequency domain decomposition technique

EFDD technique is an extension of the FDD technique. In this technique, modes are simply picked from singular value decomposition plots (SVD) calculated using spectral density spectra of the responses. As FDD technique is based on using a single frequency line from the Fast Fourier Transform analysis (FFT), precision of the estimated natural frequency depends on the FFT resolution and no modal damping is calculated in FDD. However, EFDD technique gives an improved estimation of natural frequencies and mode shapes including damping ratios (Jacobsen 2006). In EFDD technique, the SDOF Power Spectral Density (PSD) function, identified around a peak of resonance, is taken back to the time domain using the inverse discrete Fourier transform. 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 (Jacobsen 2006). In FDD technique, the relationship between the unknown input $x(t)$ and the measured responses $y(t)$ can be expressed as following Bendat (2004)

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

where; $G_{xx}(j\omega)$, rxr Power Spectral Density (PSD) matrix of the input, r is the number of inputs, $G_{yy}(j\omega)$ mxm PSD matrix of the responses, m is the number of responses, $H(j\omega)$, mxr Frequency Response Function (FRF) matrix, and * and superscript T denote complex conjugate and transpose, respectively. The FRF can be written in partial fraction, i.e., pole/residue form

$$H(j\omega)=\sum_{k=1}^{n}\frac{R_k}{jw-\lambda_k}+\frac{R_k^{*}}{jw-\lambda_k^{*}} \tag{2}$$

where; n, number of modes, λ_k, pole, and R_k, residue, Then Eq. (1) becomes (Brincker *et al.* 2000)

$$G_{yy}(j\omega)=\sum_{k=1}^{n}\sum_{s=1}^{n}\left[\frac{R_k}{jw-\lambda_k}+\frac{R_k^{*}}{jw-\lambda_k^{*}}\right]\left[G_{xx}(j\omega)\right]\left[\frac{R_k}{jw-\lambda_k}+\frac{R_k^{*}}{jw-\lambda_k^{*}}\right]^{H} \tag{3}$$

where; s, singular values and superscript H denotes complex conjugate and transpose. Multiplying the two partial fraction factors and making use of the Heaviside partial fraction theorem, after some mathematical manipulations, the output PSD can be reduced to a pole/residue form as follows (Brincker *et al.* 2000)

$$G_{yy}(j\omega)=\sum_{k=1}^{n}\frac{A_k}{jw-\lambda_k}+\frac{A_k^{*}}{jw-\lambda_k^{*}}+\frac{B_k}{-jw-\lambda_k}+\frac{B_k^{*}}{-jw-\lambda_k^{*}} \tag{4}$$

where; A_k, k_{th} residue matrix of the output PSD. In the EFDD identification, the first step is to estimate the PSD matrix. The estimation of the output PSD $G_{yy}(j\omega)$ known at discrete frequencies $w=w_i$ is then decomposed by taking the SVD of the matrix (Brincker *et al.* 2000).

$$G_{yy}(j\omega_i)=U_iS_iU_i^{H} \tag{5}$$

where; matrix $U_i=u_{i1}, u_{i2}, \ldots, u_{im}$, unitary matrix holding the singular vectors u_{ij} and S_i, diagonal matrix holding the scalar singular values s_{ij}. Thus, in this case, the first singular vector u_{ij} is an estimation of the mode shape. PSD function is identified around the peak by comparing the mode shape estimation u_{ij} with the singular vectors for the frequency lines around the peak. As long as a singular vector is found, which has a high modal assurance criterion (MAC) value with u_{ij}, the corresponding singular value belongs to the SDOF density function. From the piece of the SDOF density function obtained around the peak of the PSD, the natural frequency and the damping can be obtained (Brincker *et al.* 2000).

2.2 Stochastic subspace identification technique

Stochastic Subspace Identification Technique (SSI) is an output-only time domain method (Van and De Moor 1996, Peeters and De Roeck 1999, Peeters 2000). In this technique, structures can be defined by a set of linear constant coefficient and second order differential equations as given below (Peeters and De Roeck 1999).

$$M\ddot{U}(t)+C_*\dot{U}(t)+KU(t)=F(t)=B_*u(t) \tag{6}$$

where; M, C_* and K, mass, damping, and stiffness matrices, $F(t)$, excitation force, and $U(t)$, displacement vector at continuous time t.

The force vector $F(t)$ is factorized into a matrix B_* describing the inputs in space and a vector $u(t)$. Although Eq. (6) represents quite closely the true behavior of a vibrated structure, it is not directly used in SSI methods. Thus, Eq. (6) will be converted to a more suitable form: The discrete-time stochastic state-space model (Peeters and De Roeck 1999). With the following definitions

$$x(t)=\begin{pmatrix} U(t) \\ \dot{U}(t) \end{pmatrix},\ A=\begin{pmatrix} 0 & I_{n_2} \\ -M^{-1} & -M^{-1}B_* \end{pmatrix},\ B=\begin{pmatrix} 0 \\ M^{-1}B_* \end{pmatrix} \tag{7}$$

Eq. (6) can be transformed into the state equation

$$\dot{x}(t)=Ax(t)+Bu(t) \tag{8}$$

where; A, state matrix, B, input matrix, and $x(t)$, state vector.

The number of elements of the state-space vector is the number of independent variables needed to describe the state of a system. If it is assumed that the measurements are evaluated at only one sensor locations and this sensor can be an accelerometer or velocity or displacement transducer, the observation equation is (Juang 1994)

$$y(t)=Cx(t)+Du(t) \tag{9}$$

where; C, output matrix and D, direct transmission matrix.

Eq. (8) and (9) constitute a continuous time deterministic state-space model. Continuous time means that the expressions can be evaluated at each time instant $t\in R$ and deterministic means that the input-output quantities $u(t)$ and $y(t)$ can be measured exactly. Of course, this is not realistic: Measurements are available at discrete-time instants $k\Delta t$, $k\in N$ with Δt as the sample time, and noise is always influencing the data. After sampling, the state-space model looks like (Peeters 2000).

$$\left.\begin{aligned} x_{k+1} &= Ax_k + Bu_k \\ y_k &= Cx_k + Du_k \end{aligned}\right\} \tag{10}$$

where; $x_k=x(k\Delta t)$, discrete-time state vector.

The stochastic components (noise) are included and obtained in the following discrete-time combined deterministic-stochastic state-space model

$$\left.\begin{aligned} x_{k+1} &= Ax_k + Bu_k + w_k \\ y_k &= Cx_k + Du_k + v_k \end{aligned}\right\} \tag{11}$$

where; w_k, process noise due to disturbances and modeling inaccuracies and v_k, measurement noise due to sensor inaccuracy.

They are both immeasurable vector signals, but it is assumed that they are zero mean, white, and with covariance matrices (Peeters De Roeck 1999)

$$E\left[\begin{pmatrix} w_p \\ v_p \end{pmatrix}\begin{pmatrix} w_q^T & v_q^T \end{pmatrix}\right] = \begin{pmatrix} Q & S \\ S^T & R \end{pmatrix}\delta_{pq} \tag{12}$$

where; E, expected value operator and δ_{pq}, Kronecker delta.

The Kronecker delta is a function of two variables, usually integers, which is 1 if they are equal and 0 otherwise. So, it can be written as the symbol δ_{pq} and treated as a notational shorthand rather than as a function

$$\delta_{pq} = \begin{cases} 1 \text{ if } p = q \\ 1 \text{ if } p \neq q \end{cases} \tag{13}$$

Due to the lack of input information, it is impossible to distinguish deterministic input u_k from the noise terms w_k and v_k in Eq (11). If the deterministic input term u_k is modeled by the noise terms w_k and v_k, the discrete-time purely stochastic state-space model of a vibration structure is obtained (Yu and Ren 2005).

$$\left.\begin{aligned} x_{k+1} &= Ax_k + w_k \\ y_k &= Cx_k + v_k \end{aligned}\right\} \tag{14}$$

Eq. (14) constitutes the basis for the time domain system identification through operational vibration measurements. The SSI method identifies the state-space matrices based on the output-only measurements and by using robust numerical techniques (Sevim *et al*. 2010b).

3. Descriptions of RC frames and mixture proportion of low strength concrete

As stated before, in this study, dynamic characteristics of a full scaled, one bay and one story brick in-filled RC frame with low strength were determined for plane, brick in-filled and brick in-filled with plaster conditions using ambient vibration test. 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 of frame is given in Table 1. CEM II/B-M (P-LL) 32.5R was used as cement and dosage was kept constant at 250 kg/m3 with 0.9 W/C ratios. Characteristic compressive strength and elasticity modulus of the concrete is 9.75 MPa and 11245 MPa, respectively.

Table 1 Mixture proportions of low strength concrete

Mixture proportions	Quantities of Aggregates (kg/m3)					Saturation Water (kg/m3)	Mixing Water (kg/m3)	Cement (kg/m3)
	Sieve Size (mm)							
	0.5-1.0	1.0-2.0	2.0-4.0	4.0-8.0	8.0-16.0			
	265.35	265.35	265.35	442.25	530.40	7.076	225	250

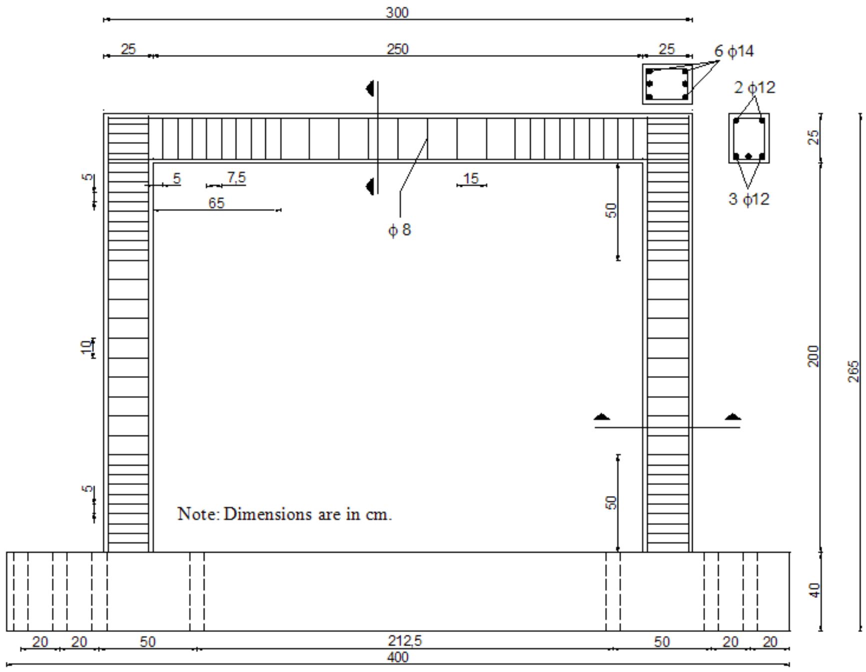

Fig. 1 Dimensions and reinforcement details of the RC frame with low strength

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

Ambient vibration tests were conducted on RC frame with low strength to determine its dynamic characteristics. Measurements were carried out for plane, brick in-filled and in-filled with plaster. Tests were performed using B&K8340 type uni-axial accelerometers. During the tests, frequency span was selected as 0.1-300 Hz. The measurements were taken for 15min and excitations were provided from small impact effects. 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 and SSI techniques.

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. 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 and schematic view of accelerometer locations for plane frame are given in Fig. 2.

Singular values of spectral density matrices (SVSDM) and average of auto spectral densities (AASD) of the data set obtained from EFDD technique and stabilization diagrams of estimated

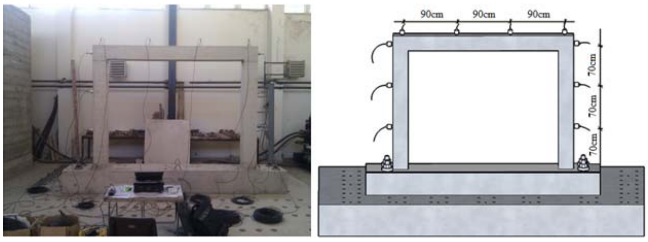

Fig. 2 Ambient vibration tests and schematic views of accelerometer locations for plane frame

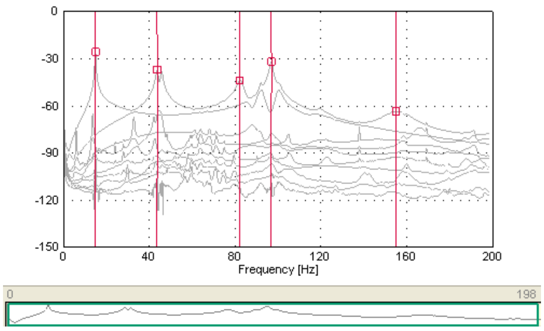

Fig. 3 SVSDM and AASD of the data set for plane frame with low strength

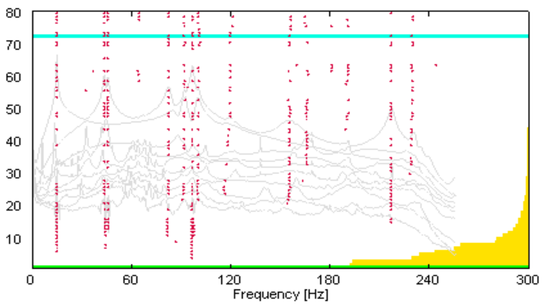

Fig. 4 Stabilization diagrams of estimated state-space models for plane frame

Table 2 Natural frequencies and damping ratios of plane frame with low strength

Modes	Natural Frequencies (Hz)	Modal Damping Ratios %
1	14.99	1.088
2	43.71	1.280
3	82.37	1.492
4	96.91	0.700
5	155.20	2.911

state-space models using SSI method are shown in Fig. 3 and Fig. 4, respectively.

In Fig. 3, peak values are vibration resonances of the frame and frequency value for each resonance shows natural frequencies. Five natural frequencies are obtained between 14-155Hz frequency span by evaluating Fig. 3 and 4 together. Modal damping ratios are obtained by using these frequencies at peak values. The first five mode shapes of plane frame with low strength are

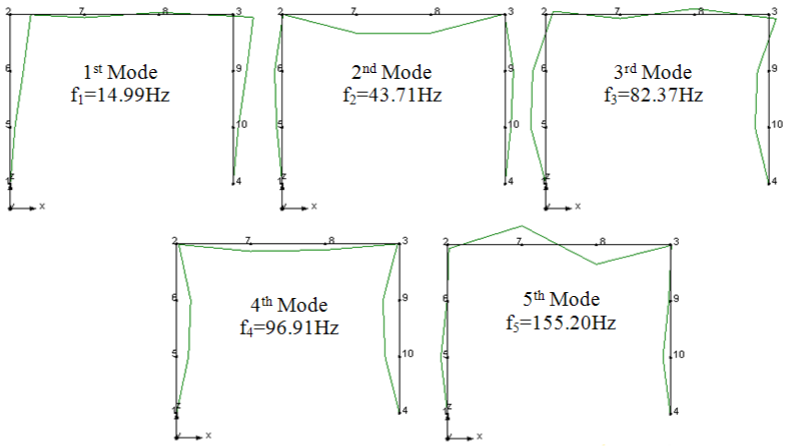

Fig. 5 The first five mode shapes of plane frame

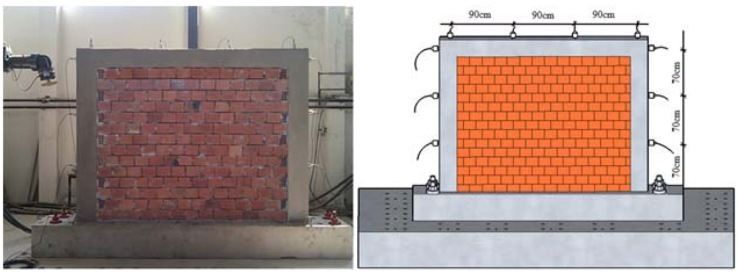

Fig. 6 Ambient vibration tests and schematic views of accelerometer locations for brick in-filled frame

seen Fig. 5 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 with low strength to determine effects of construction stages on dynamic characteristics. As infill materials, brick having 13.5×19×19 cm dimensions were used. Average compressive strength and elasticity modulus of brick are 5.2MPa and 4000MPa, respectively. Compressive strength of mortar used in in-filled wall is 4.52MPa. 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 Fig. 6.

Singular values of spectral density matrices (SVSDM) and average of auto spectral densities (AASD) of the data set obtained from EFDD technique and stabilization diagrams of estimated state-space models using SSI method are shown in Fig. 7 and Fig. 8, respectively. As seen in Fig. 7, five natural frequencies are obtained clearly between 56-217 Hz frequency span.

The first five mode shapes of brick in-filled frame are seen Fig. 9 and natural frequencies and modal damping ratios obtained from the tests are given in Table 3. These results show that infill walls increase reasonably frequencies and stiffness of RC frame. Mode shapes of the frame are different compared to plane frame except for first mode.

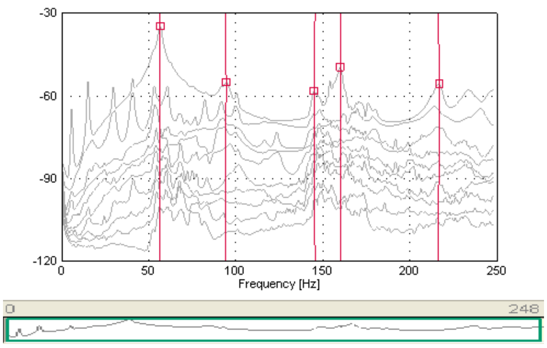

Fig. 7 SVSDM and AASD of the data set for brick in-filled frame

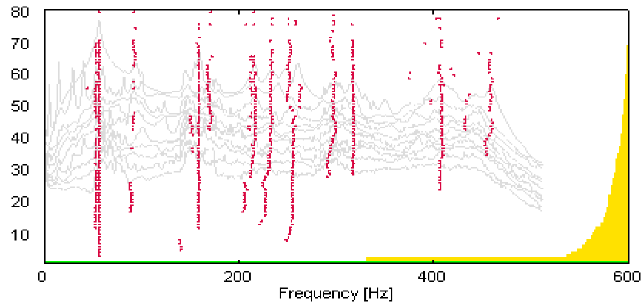

Fig. 8 Stabilization diagrams of estimated state-space models for brick in-filled frame

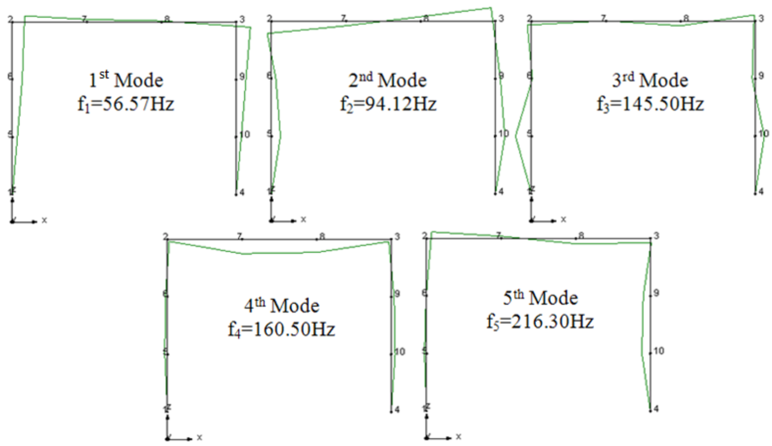

Fig. 9 The first five mode shapes of brick in-filled frame with low strength

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

Modes	Natural Frequencies (Hz)	Modal Damping Ratios (%)
1	56.57	2.197
2	94.12	2.084
3	145.50	0.943
4	160.50	0.820
5	216.30	0.913

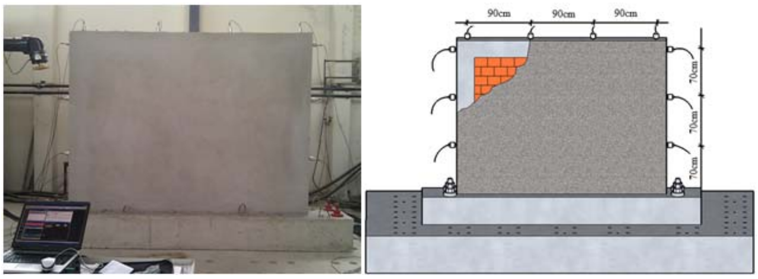

Fig. 10 Ambient vibration tests and schematic views of accelerometer locations for brick in-filled RC frame with plaster frame

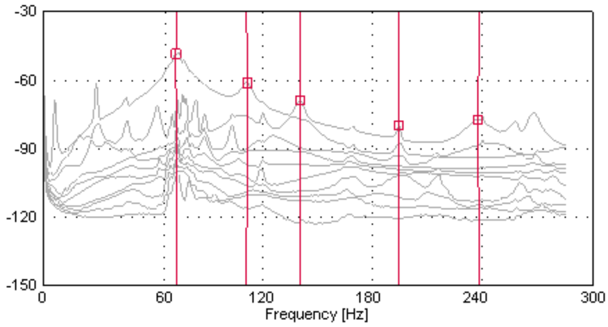

Fig. 11 SVSDM and AASD of the data set for brick in-filled with plaster frame

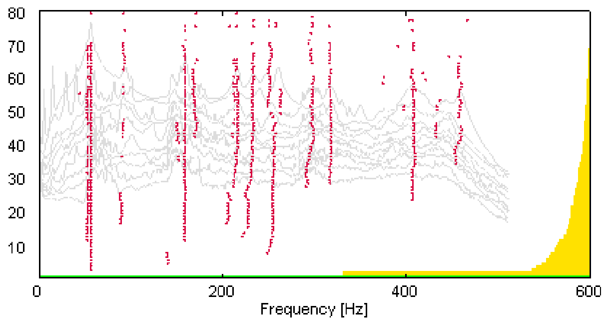

Fig. 12 Stabilization diagrams of estimated state-space models for brick in-filled frame with plaster

5.3 Brick in-filled frame with plaster measurements

Finally, OMA with ambient vibrations have been carried out on brick in-filled RC frame with plaster 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 RC frame with plaster and schematic view of accelerometer locations are given in Fig. 10.

Singular values of spectral density matrices (SVSDM) and average of auto spectral densities (AASD) of the data set obtained from EFDD technique and stabilization diagrams of estimated state-space models using SSI method are shown in Fig. 11 and Fig. 12, respectively. It is seen from Fig. 11, five natural frequencies are obtained clearly between 65-240 Hz frequency span.

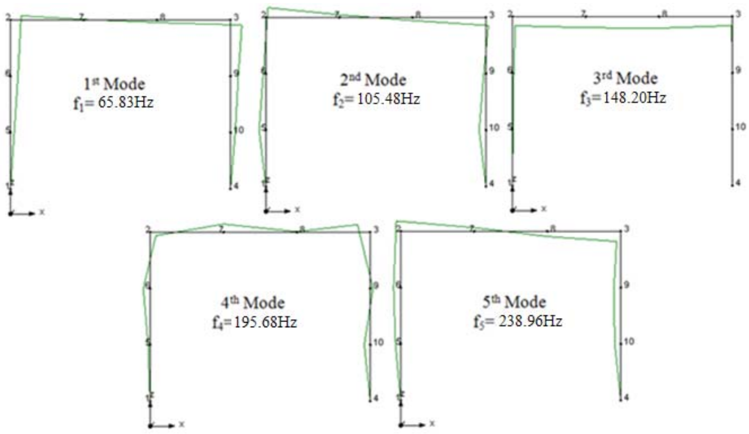

Fig. 13 The first five mode shapes of brick in-filled with plaster frame

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

Modes	Natural Frequencies (Hz)	Modal Damping Ratios (%)
1	65.83	4.237
2	105.48	1.828
3	148.20	1.680
4	195.68	0.401
5	238.96	1.194

The first five mode shapes of brick in-filled with plaster frame are seen Fig. 13 and natural 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.

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 14-240Hz. By considering the first five mode shapes, these modes can be classified into bending and lateral modes.

• The first fifth natural frequencies are obtained between 14-156Hz, 56-217Hz and 65-240Hz for plane, brick in-filled and in-filled with plaster conditions, respectively.

• Infill 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.

Consequently, in-filled walls change dynamic behavior of RC frame. In addition, damping ratios of the frame for each mode increases with the existence of the infill walls. These results show that effects of infill 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 infill walls do not necessarily means that we stay on the safe side for every time. 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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