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Finite element model updating of in-filled RC frames with low strength concrete using ambient vibration test

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Abstract. This paper describes effects of infill walls on behavior of RC frame with low strength, including numerical modeling, modal testing and finite-element model updating. For this purpose full scaled, one bay and one story RC frame is produced and tested for plane and brick in-filled conditions. Ambient-vibration testis applied to identify dynamic characteristics under natural excitations. Enhanced Frequency Domain Decomposition and Stochastic Subspace Identification methods are used to obtain experimental dynamic characteristics. A numerical modal analysis is performed on the developed two-dimensional finite element model of the frames using SAP2000 software to provide numerical frequencies and mode shapes. Dynamic characteristics obtained by numerical and experimental are compared with each other and finite element model of the frames are updated by changing some uncertain modeling parameters such as material properties and boundary conditions to reduce the differences between the results. At the end of the study, maximum differences in the natural frequencies are reduced on average from 34% to 9% and a good agreement is found between numerical and experimental dynamic characteristics after finite-element model updating. In addition, it is seen material properties are more effective parameters in the finite element model updating of plane frame. However, for brick in-filled frame changes in boundary conditions determine the model updating process.

Keywords: ambient vibration; dynamic characteristics; finite-element model updating; low strength concrete; RC frames

1. Introduction

Finite element modeling of engineering structures requires professional engineering knowledge in the design phase to determine structural behavior. However, material properties, boundary conditions and section properties accepted in the analyses can be changed by some reasons such as application mistakes, insufficient material usage required for project. In addition, during construction, the structure can be exposed to different load cases which are not considered in the design. These reasons make difficult to define the exact material properties and determine real behavior of the structures. Therefore, performance of the structures should be controlled by the help of field testing or experimental measurements. Generally, dynamic characteristics such as natural frequencies and mode shapes obtained from field testing do not coincide with those of the numerical model. Here, model updating is required to modify the numerical model by using

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experimental measurements (Jaishi and Ren 2005, Altunışık *et al.* 2011a).The main purpose of the model updating procedure is to minimize the differences between the numerically and experimentally determined dynamic characteristics by changing some uncertainty parameters such as material properties or boundary conditions.

As mentioned earlier, numerical dynamic characteristics don't reflect the actual characteristics of the current structure. Therefore, experimental methods are needed to verify accuracy of numerical results or update dynamic characteristics and calculate earthquake forces. There are many studies are available in technical literature on experimental methods. 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) (Cantieni 2004).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 (Roeck *et al.* 2000, Sevim *et al.* 2010).

RC frame system is one of the most popular structural systems used for construction of reinforced concrete short buildings. RC frames are often in-filled with brick or concrete-block masonry for functional reasons (Klingner and Bertero 1978, Maharani *et al.* 1996, FEMA 356 2000, Sahoo and Rai 2010). Dynamic characteristics such as natural frequencies, mode shapes and damping ratio are significantly influenced by infill walls. When the natural frequencies, computed using empirical formulas were compared with measured natural frequencies, errors greater than ±50% were observed (Ellis 1980). For these reasons, the dynamic characteristics of in-filled frames should be determined by taking into account effects of infill. Experimental and theoretical studies on in-filled frames (Kodur *et al.* 1995) indicated that presence of infill walls cause significant changes in the dynamic characteristics of buildings and influence their behavior during earthquakes. Thus, 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.

In this study, modal testing and finite-element model updating of RC frame with low strength concrete to determine effects of infill walls on behavior of RC frame using OMA under ambient vibration are studied. Background reviews of existing literature related to the numerical and experimental investigations of structures are briefly mentioned. This is followed by finite-element model updating procedures. Then, the formulation of enhanced frequency domain decomposition (EFDD) and stochastic subspace identification (SSI) methods, which are used to extract modal parameters experimentally, is given in detail. Then, the RC frame is described. Also, the initial finite element model and main assumptions made during its development are presented. Afterwards, experimental modal characteristics are compared with the numerical results. Finally finite-element models are manually updated and key results of the tests are discussed.

2. Background review

2.1 Modal testing

Modal testing is needed to verify accuracy of numerically determined dynamic characteristics and calculate earthquake forces structure is subjected to. Modal testing is directly applied on the structures to obtain current dynamic behaviors. Modal testing of structures is not a recent practice, and many studies have been carried out in the past. Modal tests were used initially advanced mechanical and aerospace engineering disciplines (Ewins 1984, Juang 1994, Maia and Silva 1997, Bayraktar *et al.* 2009). There are many studies are available in technical literature on modal testing, after adopting the test method to civil engineering problems, (Zhou *et al.* 2000, Chang *et al.* 2001, Reynolds *et al.* 2004, Sortis *et al.* 2005, Dooms *et al.* 2006, Zivanovic *et al.* 2006, Gentile and Saisi 2007, Wang and Li 2007, Bayraktar *et al.* 2010a).

2.2 Finite-element model updating procedure

In numerical analysis of structures, so much effort is devoted to constitute more accurate models. In the development of finite element models of structures, it is common to make assumptions simplify. It has been seen by the help of field dynamic tests performed to validate the finite element model, natural frequencies and mode shapes; they do not coincide with the expected results from the numerical model. These inconsistencies originate from the uncertainties in simplifying assumptions of the structural geometry, materials, and inaccurate boundary conditions. The study of how to modify the numerical model from the dynamic measurements is known as the model updating in structural dynamics (Jaishi and Ren 2005). The main purpose of the model updating procedure is to minimize the differences between the numerically and experimentally obtained modal properties by changing uncertainty parameters such as material properties and boundary conditions (Bayraktar *et al.* 2011).

The updating process typically consists of manual tuning and then automatic model updating using some specialized software. The manual tuning involves manual changes of the model geometry and modeling parameters by trial and error, guided by engineering judgments. The aim of this is to bring the numerical model closer to the experimental one (Zivanovic *et al.* 2007). In this study, the manual tuning procedure is used for finite element model updating (Bayraktar *et al.* 2011). Over the last decade; there have been several attempts to transfer the updating technology from mechanical and aerospace engineering to civil structural engineering. Although the whole is more difficult to implement in civil engineering, some successful examples of updating in civil engineering can be seen for bridges (Zhang *et al.* 2001), buildings (Lord *et al.* 2004), minarets (Bayraktar *et al.* 2007), and high-rise structures (Wu and Li 2004).

2.3 Modal parameters identification 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 *et al.* 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.

2.3.1 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 *et al.* 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 *et al.* 2006). In EFDD technique, the relationship between the unknown input x(t) and the measured responses y(t) can be expressed as following, (Bendat and Piersol 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: $G_{yy}(j\omega)$ = 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. Detailed information about the EFDD method can be found in the literature (Felber 1993, Brincker *et al.* 2000, Peeters 2000, Rainieri *et al.* 2007, Altunışık *et al.* 2011b).

2.3.2 Stochastic subspace identification technique

SSI is an output-only time domain method that directly works with time data, without the need to convert them to correlations or spectra. The method is especially suitable for operational modal parameter identification (Bayraktar *et al.* 2010b).

The model of vibration structures can be defined by a set of linear, constant coefficient, and second-order differential equations (Van Overschee and De Moor 1996, Peeters 2000, Juang and Phan 2001).

$$M\ddot{U}(t)+C_{*}\dot{U}(t)+KU(t)=F(t)=B_{*}u(t) \tag{2}$$

Where, M, C_{*} and K: mass, damping, and stiffness matrices (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. (2) represents quite closely the true behavior of a vibrated structure, it is not directly used in SSI methods. Thus, Eq. (2) will be converted to a more suitable form: The discrete-time stochastic state-space model. The state-space model originates from control theory; but it also appears in mechanical/civil engineering to compute the modal parameters of a dynamic structure with a general viscous damping model (Ewins 1984). In the literature solution of the Eq. (2) is given in detail (Juang 1994, Yu and Ren 2005).

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

In this study, modal testing and finite-element model updating of plane and in-filled RC frame with low strength concrete using OMA under ambient vibration are studied comparatively. 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) 32.5R was used as cement and dosage was kept constant at 250kg/m3 with 0.9W/C ratios. Characteristic compressive strength and elasticity modulus of the concrete is 9.75MPa and 11245MPa, 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

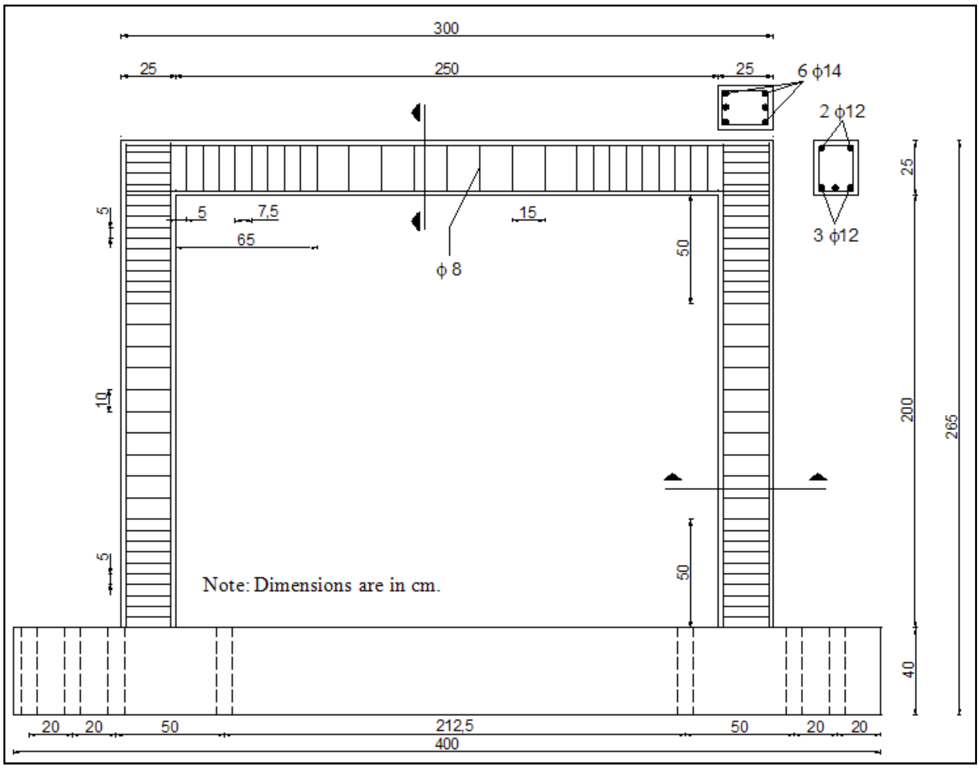

Fig. 1 Dimensions and reinforcement details of the RC frame with low strength

4. Finite element modeling, ambient vibration test and modal identification

Ambient vibration tests were conducted on RC plane and brick in-filled frames with low strength to determine its dynamic characteristics. 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 (OMA 2006). The dynamic characteristics of frame for different construction stage were extracted by EFDD and SSI techniques.

4.1 Finite-element modeling

In this paper, the 2D linear elastic finite-element model (Fig. 2) of the RC frames with low strength were generated using the software SAP2000 (2008) to determine the dynamic characteristics of the plane and in-filled frames based on the physical and mechanical properties. The values of the material properties used in analyses of the RC frame with low strength are given in Table 2.Elasticity modulus of brick infill was taken from the technical literature (Beklen 2009).

The key modeling assumptions are as follows:

- The RC frame was expected as plane frame; namely rotations around X axis and Z axis, translation at Y axis of the frame were restricted;
- The brick infill wall was modeled using shell elements;
- The supports of the frame were modeled as fully fixed and springs having 6E9N/m rigidity at global Z direction were assigned to the bottom side of infill wall;
- The members of the frame were modeled as rigidly connected together at the intersection points.

The first five mode shapes obtained from finite-element analysis of plane and in-filled frames appear in Figs. 3 and 4, respectively.

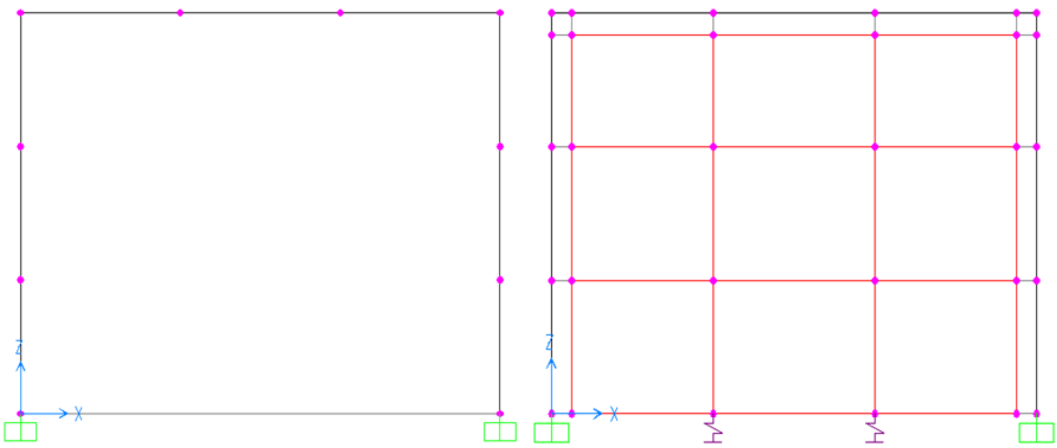

Fig. 2 Finite-element models of plane and brick in-filled RC frames

Table 2 Some mechanical and physical properties of materials used in analyses

Material	Modulus of elasticity (N/m2)	Poisson's ratio	Mass per unit vol. (kg/m3)
Steel	2.000E11	0.3	7900
Concrete	1.125E10	0.2	2345
Brick	2.000E9	0.2	600

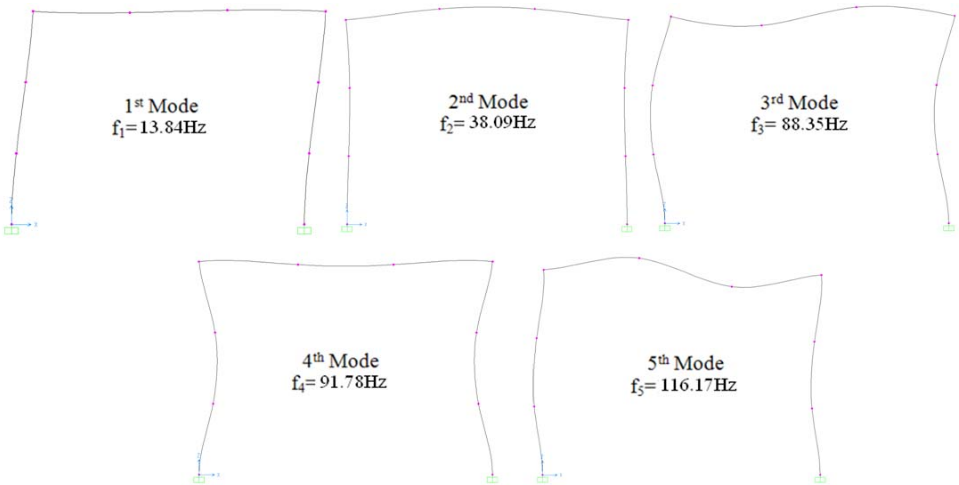

Fig. 3 Numerically identified mode shapes of the plane frame

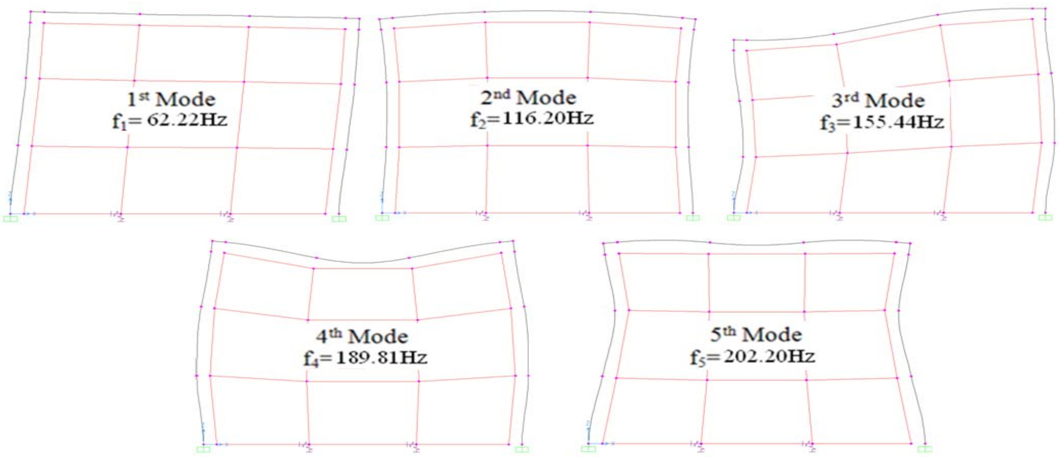

Fig. 4 Numerically identified mode shapes of the in-filled RC frame

4.2 Ambient vibration testing and modal identification of plane frame

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 plans of accelerometers for plane frame are given in Fig. 5. During the tests 1024Hz sampling frequency has been used and to decrease effects of sounds and other vibrations High Pass Filtering value has been chosen as 0,7Hz. In EFDD technique, ten channels were used. Amount of data point per channels are 917504, namely totally 9175040 data have been used for the tests. Duration of tests was approximately 896 sec. on the other hand; hanning window has been used as windowing function.

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 Figs. 6 and 7, respectively.

In Fig. 6, peak values are vibration resonances of the frame and frequency value for each resonance shows natural frequencies. Five natural frequencies are obtained between 14-156Hz frequency span by evaluating Fig. 6 and Fig. 7 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 seen Fig. 8 and natural frequencies and modal damping ratios obtained from the tests are given in Table 3.

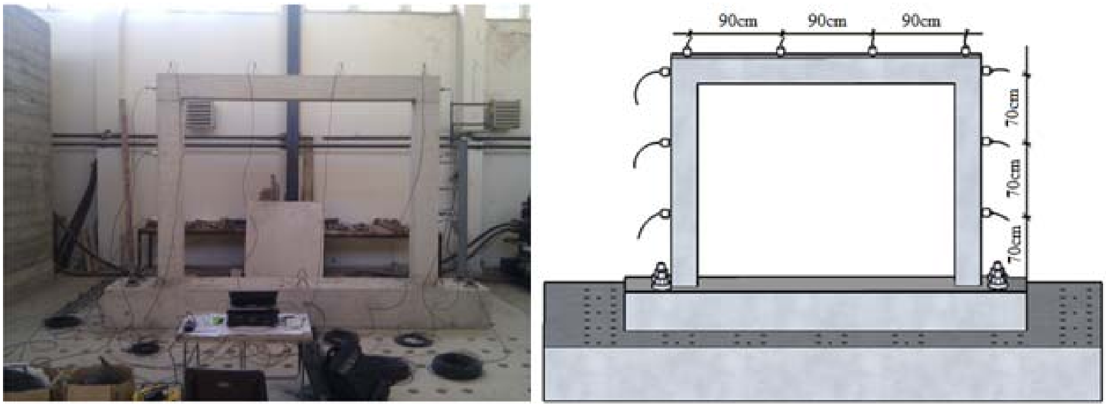

Fig. 5 Ambient vibration tests and plans of accelerometers for plane frame

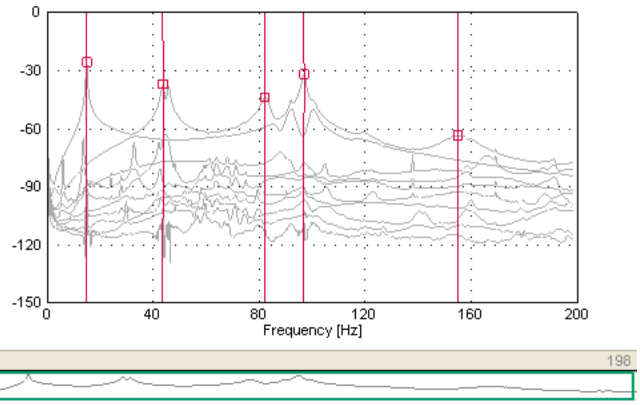

Fig. 6 SVSDM and AASD of the data set for plane frame with low strength

Table 3 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

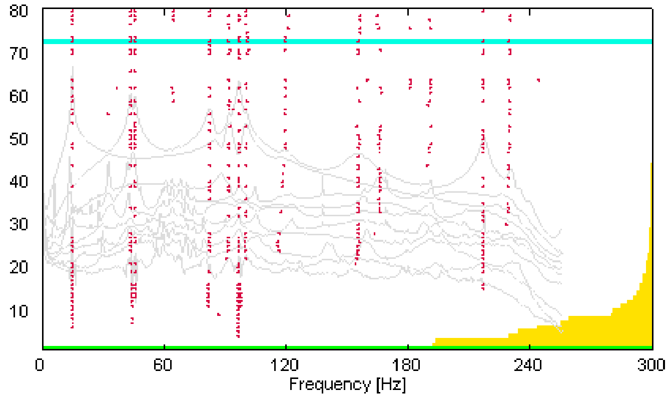

Fig. 7 Stabilization diagrams of estimated state-space models for plane frame

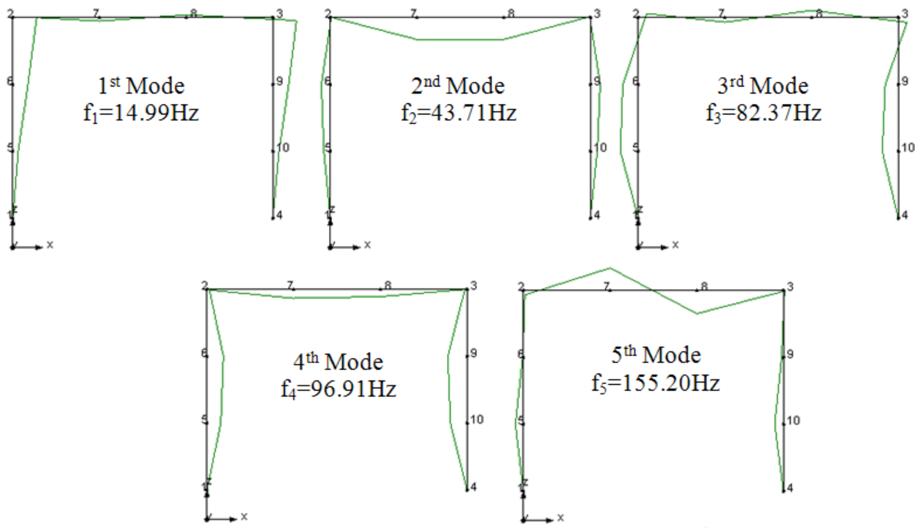

Fig. 8 Experimentally identified the first five mode shapes of plane frame

4.3 Ambient vibration testing and modal identification of brick in-filled frame

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 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 plans of accelerometers are given in Fig. 9.

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 Figs. 10 and 11, respectively. As seen in Fig. 10, 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. 12 and natural frequencies and modal damping ratios obtained from the tests are given in Table 4. 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.

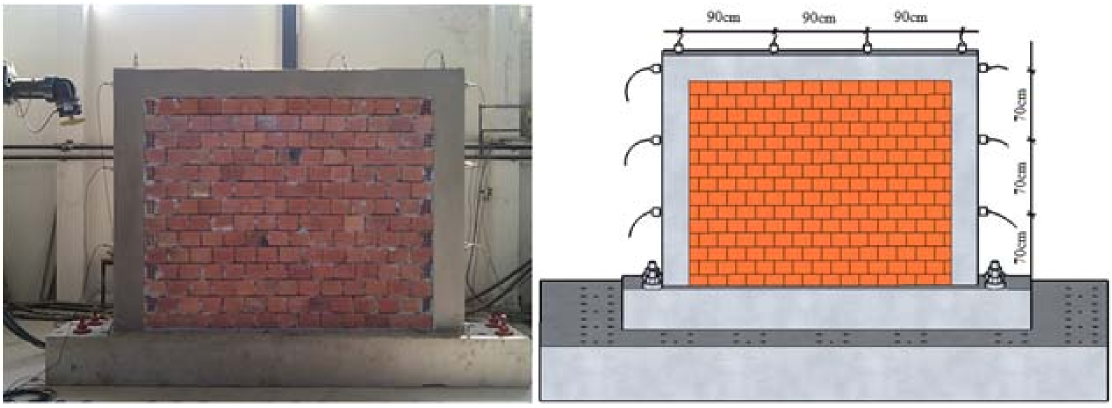

Fig. 9 Ambient vibration tests and plans of accelerometers for brick in-filled frame

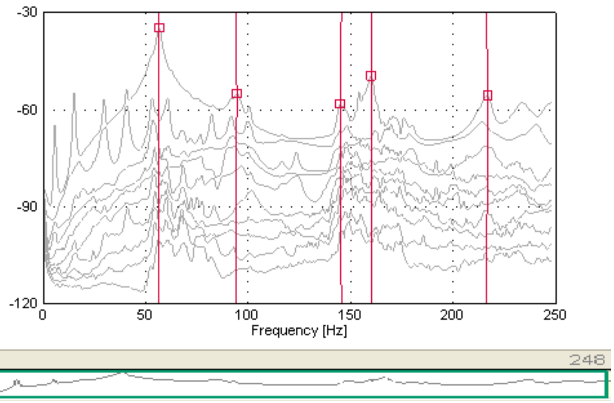

Fig. 10 SVSDM and AASD of the data set for brick in-filled frame

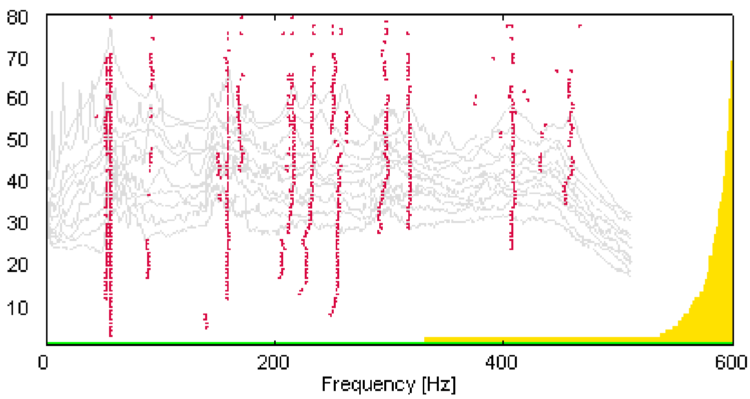

Fig. 11 Stabilization diagrams of estimated state-space models for brick in-filled frame

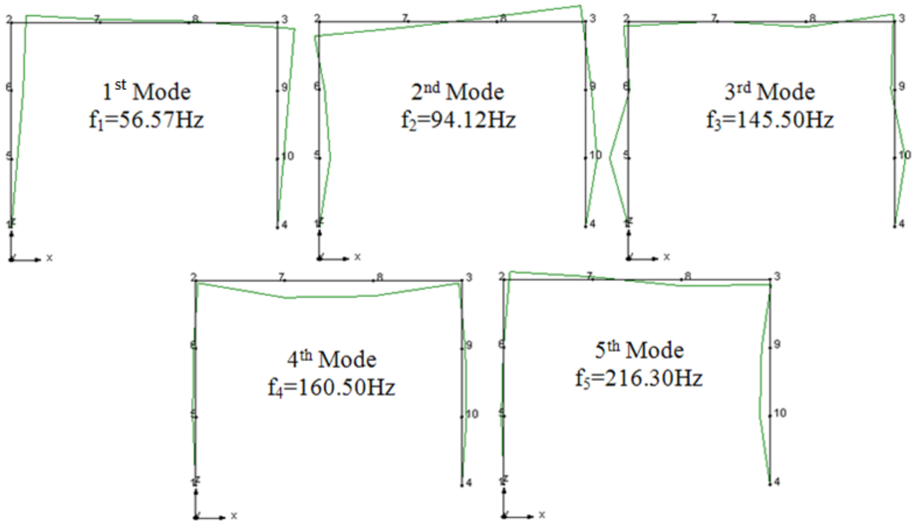

Fig. 12 Experimentally identified the first five mode shapes of brick in-filled frame

Table 4 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

5. Finite-element model updating

It can be seen from Table 3 and Table 4 that there are some differences between results obtained from numerical and experimental modal analyses of plane and brick in-filled frames. It is thought that these differences come from some uncertainties in the structural geometry, material properties, and boundary conditions. For these reasons, the finite-element model of the frames must be updated. The main purpose of the model updating procedure is to minimize the differences between the numerically and experimentally obtained modal properties by changing uncertainty parameters such as material properties and boundary conditions. The updating process typically consists of manual tuning and then automatic model updating using some specialized software. The manual tuning involves manual changes of the model geometry and modeling parameters by trial and error, guided by engineering judgments. The aim of this is to bring the numerical model closer to the experimental one. In this study, the manual tuning procedure was used for finite element model updating and the finite element models of the frames were updated by changing the material properties and boundary conditions. Boundary conditions at the supports of frame were defined using spring elements. The values of spring stiffness are assumed as 1.2E9N/m at X direction 6E9N/m at Z directions and 6E9N/m at rotation. Changing material properties of structural elements for model updating the plane frame are given in Table 5. Frequency values obtained from numerical and experimental modal analyses after model updating of the finite-element model of the frames are given in Table 6. The first five mode shapes of plane and brick in-filled frames are seen in Figs. 13 and 14, respectively.

Table 5 Change in material properties of structural elements for model updating

Cross-Sectional Properties	Before finite-element model updating		After finite-element model updating	
	Modulus of elasticity (N/m^2)	Mass per unit volume (kg/m^3)	Modulus of elasticity (N/m^2)	Mass per unit volume (kg/m^3)
Steel rebar	2.000E11	7,900	2.000E11	7,900
Concrete	1.125E10	2,400	1.325E10	2,420
Brick infill	2.000E9	600	2.125E9	700

Table 6 Frequencies of experimental and updated numerical models of the frames

Specimen	Numerical (Hz)	Updated numerical (Hz)	Experimental (Hz)	Experimental/ umerical	Experimental/ Updated Numerical
Plane Frame	13.84	14.90	14.99	1.08	1.01
	38.09	41.02	43.71	1.14	1.06
	88.35	90.29	82.37	0.93	0.92
	91.78	98.17	96.91	1.05	0.99
	116.17	141.26	155.20	1.34	1.09
Brick In-filled Frame	62.22	56.65	56.57	0.91	1.00
	116.20	101.80	94.12	0.81	0.92
	155.44	144.32	145.50	0.94	1.01
	189.81	174.28	160.50	0.85	0.92
	202.20	205.64	216.30	1.07	1.05

As it is seen in Table 6, the finite-element model updating of plane and brick in-filled frames minimized the differences between numerically and experimentally estimated modal properties by changing some uncertain modeling parameters such as material properties and boundary conditions. Maximum differences in the natural frequencies are reduced on average from 34% to 9%. By this way the closest behavior and frequency values were obtained to the exact dynamic characteristics.

Modal Assurance Criteria (MAC) is added to the paper. The Modal Assurance Criteria (MAC) is defined as a scalar constant relating the degree of consistency (linearity) between one modal and another reference modal vector (Allemang, 2003) as follows

$$MAC = \frac{\left|\{\phi_{ai}\}^T\{\phi_{ej}\}\right|^2}{\{\phi_{ai}\}^T\{\phi_{ai}\}\{\phi_{ej}\}^T\{\phi_{ej}\}} \tag{3}$$

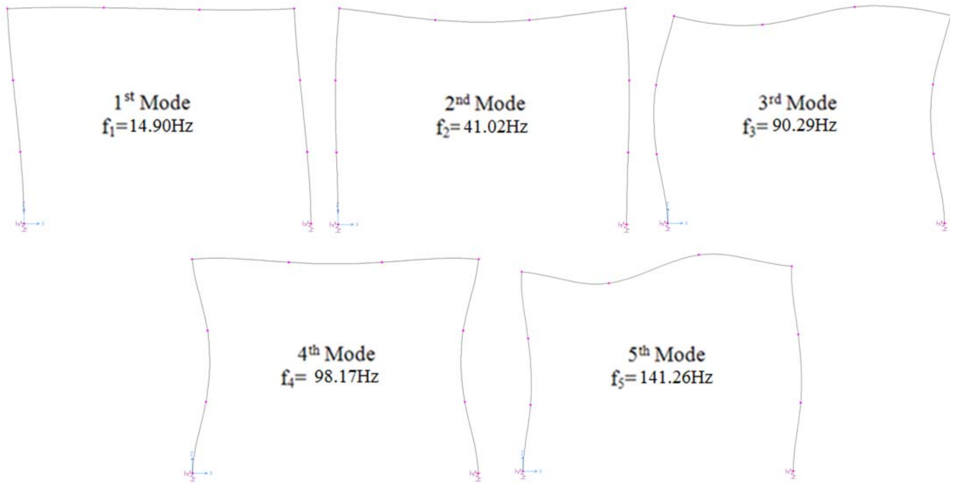

Fig. 13 Updated numerical mode shapes of plane frame

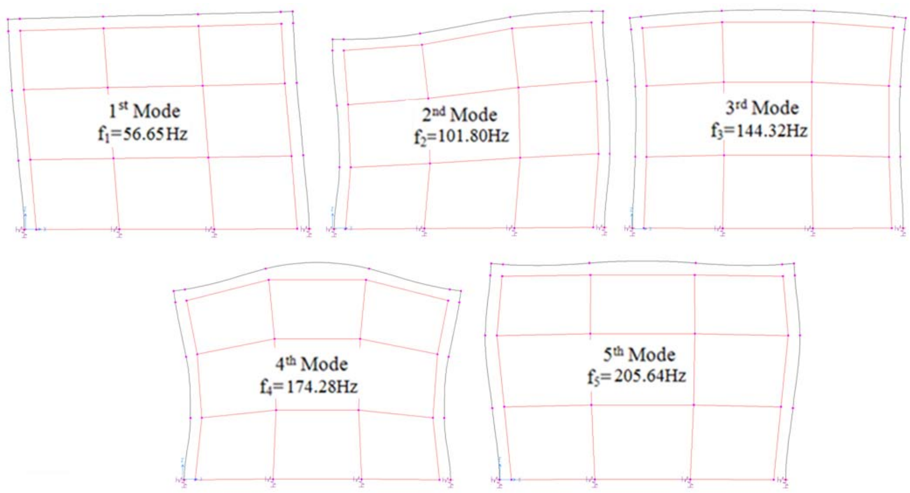

Fig. 14 Updated numerical mode shapes of brick in-filled frame

Where $\{\phi_{ai}\}$ and $\{\phi_{ej}\}$ are the modal vectors of ith and jth for different techniques, respectively.

Graphical representations of Modal Assurance Criteria (MAC) related to the plane and in-filled frame are shown in Fig. 15. As seen in Fig. 15 that MAC values are almost 90-100%. This shows that all results are almost overlapped.

Here, it should be expressed that correlation between updated model and experimental measurement has been calculated only using diagonal values of each modes by the help of Eq. (3).

6. Conclusions

In this paper, numerical modeling, modal testing, and finite element model updating of plane

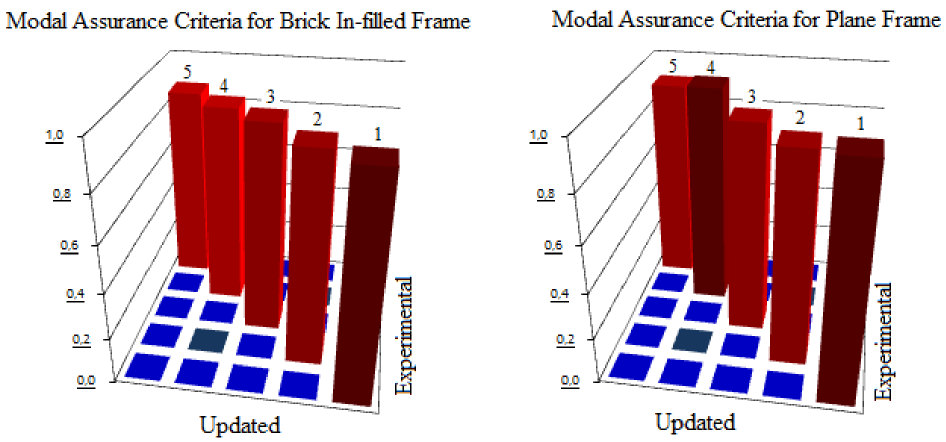

Fig. 15 Graphical representations of Modal Assurance Criteria (MAC) of the frames

and brick in-filled frames were presented. 2D finite-element model of the frames were developed using the SAP2000 program taking into account the design data, and modal parameters such as frequencies and mode shapes were determined. Ambient vibration testing was conducted under the natural excitation of the frames. Two complementary modal parameter identification methods were implemented to accurately extract the dynamic characteristics. Numerical and experimental dynamic characteristics were compared with each other and some differences were determined. The finite-element models of the frames were updated to minimize the differences between numerically and experimentally estimated modal properties by changing some uncertain modeling parameters such as material properties and boundary conditions. Based on the results of this study, the following conclusions can be made:

- From the finite-element model of plane and brick in-filled frame totally16 and 28 natural frequencies were numerically attained, respectively. Frequencies range between 13.84Hz and 822.03Hz for plane frame and 62.23Hz-1914.60Hz for brick in-filled frame. Considering the first five mode shapes, these modes can be classified into longitudinal and vertical modes.
- From the ambient vibration tests of the RC frames, a total of 5 natural frequencies were attained experimentally for plane and brick in-filled frames, which range between 14.90-141.26Hz and 56.65Hz-205.64Hz, respectively. Mode shapes of ambient vibration tests can be classified into longitudinal and vertical modes like finite-element models.
- Ambient vibration testing was conducted under natural excitation on the frames to accurately extract the dynamic characteristics using EFDD and SSI techniques. Good agreement of identified frequencies was found between these two techniques.
- Infill wall increase considerably frequencies and stiffness, also change mode shapes. Thus, dynamic behavior of plane frame is quite different from in-filled frame.
- When comparing the numerical and experimental results, it was clearly seen that there were some differences in the results, and numerical frequencies of plane frame were lower and brick in-filled frame were higher than those of the experiments. It is thought that these results stem from uncertainty of material properties and boundary conditions.
- To eliminate differences, the finite-element model of the frames were updated by trial and error method changing boundary conditions and material properties of both concrete and brick infill wall. The maximum difference in the natural frequencies was reduced from 34% to only 9%.

- Material properties are more effective parameters in the finite element model updating of plane frame. However, for brick in-filled frame changes in boundary conditions determine the model updating process.
- After the model updating, a good agreement between the frequencies and mode shapes obtained from the updated model of the frames and experimental measurements.

Consequently, infill walls change dynamic behavior of RC frame. This result shows that effects of infill walls should be considered for structural analysis. Otherwise, structures may be affected adversely by earthquake. Ignoring effects of in-fill walls do not necessarily means that we stay on the safe side for every time. In addition, this study shows importance of model updating of finite element models to obtain the closest results to the exact behavior of structures. On the other hand, it can be inferred from this study, behavior of structures quietly changes for different construction stages. Finally, while constituting finite-element models of structures, current conditions should be considered and dynamic characteristics must be corrected by updating the models using uncertain parameters such as material properties, boundary conditions and section areas.

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