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Infill wall effects on the dynamic characteristics of RC frame systems via operational modal analysis

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Abstract. This paper presents an experimental study on the dynamic characteristics of infilled reinforced concrete (RC) frames. A 1/3-scaled, one-bay, three-storey RC frame was produced and tested by using operational modal analysis (OMA). The experiments were performed on five specimens: one reference frame with no infill walls and four frames with infill walls. The RC frame systems included infill walls made of hollow clay brick, which were constructed in four different patterns. The dynamic characteristics of the patterns, including the frequency, mode shapes and damping ratios in the in-plane direction, were obtained by 6 accelerometers. Twenty-minute records under ambient vibration were collected for each model, and the dynamic characteristics were determined using the ambient vibration testing and modal identification software (ARTeMIS). The experimental studies showed that the infill walls significantly affected the frequency value, rigidity and damping ratio of the RC frame system.

Keywords: operational modal analysis; dynamic characteristics; ambient vibration; RC frames

1. Introduction

The dynamic properties of a structure play an important role in the determination of the equivalent lateral forces and the responses from natural disturbances such as wind and seismic forces. These properties include the natural frequencies, damping ratios and vibration mode shapes of a structure and can change with respect to the level of input excitation motion, as found in many previous studies.

Beams, columns and shear walls are designed to be load-carrying members in RC structures. However, neglecting non-structural components such as infill walls, claddings, stairs and foundation flexibility in numerical modelling is a common practice. Although the effect of excluding individual non-structural components on the analysis results may be negligible, the cumulative effects of several exclusions can be significant. For example, infill walls are very common in RC structures. Many researchers have studied the stiffness (Hart *et al*. 1994) and strength characteristics of infill walls under in-plane reversed cyclic loading up to failure. If structures are subjected to cyclic loads, then their strength decreases due to progressive and permanent internal damage in a material subjected to repeated loading. This damage is attributed to the propagation of internal microcracks, which results in a significant increase in irrecoverable strain (Lee and Barr 2004).

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Regular inspection and condition assessment of structures subjected to cyclic loads are necessary to determine their serviceability and reliability. Therefore, non-destructive evaluation tools should be used. Recent computer hardware and software developments allow vibration monitoring for obtaining the modal parameters of structures. One popular vibration monitoring test is the ambient vibration test (AVT), which provides the natural frequencies, mode shapes and modal damping ratios of the structures. These tests can describe the linear behaviour of structures via small vibration amplitudes. Many historical and modern structures in civil engineering have been evaluated by using AVTs (Chaker and Cherifati 1999; Pan *et al*. 2006; Ming-ge and Wei-jian 2008; Devin and Fanning 2012; Al-Nimry *et al*. 2014; Carrillo *et al*. 2014; Singh *et al*. 2014; Salameh *et al*. 2016; Zhou *et al*. 2017; Li *et al*. 2017; Varum *et al*. 2017). Traffic, wave, and wind effects and various local sources are accepted as source excitations in AVTs.

Most AVTs have been used to determine the dynamic behaviour of existing structures. However, there are a limited number of studies in the literature in which AVTs were applied to models produced under laboratory conditions. Very few of these studies consider the effect of infill walls with and without plaster. Studies regarding structures produced under laboratory conditions and subjected to AVTs are described below.

Timuragaoglu *et al*. (2015) investigated the dynamic characteristics of RC frames with and without infill walls by using classic vibration test results within the elastic limit. They constructed and tested full-scaled, one-bay, one-storey RC frames with and without infill walls. In the study, two bare frames, two autoclaved aerated concrete and two brick-infilled RC frame systems were tested by using classic modal analysis to identify the effects of the material properties on the dynamic characteristics of the system.

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Arslan and Durmuş (2013) selected full-scaled, one-bay, one-storey RC frames to investigate different construction stages such as bare, brick infilled and brick infilled with plaster. In addition, the dynamic characteristics of RC frames with low-strength concrete were determined for different construction stages using AVTs (Arslan and Durmuş 2014). Furthermore, modal testing and a finite element model (FEM) calibration of infilled RC frames were conducted. To obtain the experimental dynamic characteristics, a combination of enhanced frequency domain decomposition (EFDD) and stochastic subspace identification (SSI) techniques was used. Analytical modal analyses were performed on a two-dimensional FEM of the frames using SAP2000 software to provide analytical frequencies and mode shapes (Arslan and Durmuş 2014). Kutanis *et al*. (2017) conducted AVTs on a single-bay, two-storey, full-scaled RC frame system to measure its modal properties for cross validation with a FEM. Then, EFDD was utilized to obtain the modal parameters of the RC frame.

Turker and Bayraktar (2017) presented the effects of the construction stages (bare frame, brick wall and plastered cases) on the modal parameters of the RC buildings. For this purpose, a three-storey RC building model was constructed at 1/2 scale in the laboratory. The modal testing measurements were performed by using OMA for the bare frame, brick wall and plastered cases. The building's modal parameters at each construction stage were extracted using the EFDD technique. (Dönmez and Alper Çankaya 2013) investigated the in-plane drift behaviour of multi-storey RC frames with infill walls. For this purpose, four-storey, single-bay, 1/5-scaled RC frames were tested with/without infill walls. The frames were subjected to pseudo-static cyclic loading. In addition, impact hammer measurements were conducted to obtain the natural frequencies and modal shapes at certain drift levels. Turker (2014) designed a base slab at 1/20 scale of an actual building base. The base slab model was tested for sand, gravel and clay–silt mixture ground conditions by using AVTs. Başaran (2015a) investigated the changes on dynamic properties of a two-storey single-bay RC building having different stirrup spacing in columns. Two RC buildings measuring 1500×1500×1350 mm were produced for testing in the study. Dynamic properties of both buildings were determined, experimentally by using the OMA and numerically by using the ABAQUS. The effect of stirrup densification in columns on dynamic properties of the building was defined by comparing both experimental and numerical analysis results. Başaran (2015b) investigated the effect of repair mortar on the dynamic properties such as natural frequencies, mode shape and damping ratios of two-storey single-bay scale RC building. The changes on the dynamic properties of repaired structure were re-evaluated by the experimental and numerical results on same models in Başaran (2015a). Abdelkrim *et al*. (2011) determined the natural frequencies of concrete beams for both damaged and undamaged situations both experimentally and numerically. This study determined the effect of the accelerometer placement distance on the natural frequency by placing the accelerometer at different distances from the crack.

In previous studies, researchers generally investigated the effect of infill walls on the dynamic behaviour of existing structures or produced laboratory conditions by using OMA. In these cases, the RC frame systems were constructed under laboratory conditions, and the researchers investigated the frames for only two extreme conditions: bare frame and fully infilled frame systems. Based on the best knowledge of the authors, the effects of infill walls in different patterns in each storey have not yet been investigated. Therefore, the studied model was a 1/3-scaled, one-bay, three-storey RC plane frame. The structural behaviour of these RC frame systems was investigated by the OMA method for 5 different cases. Two of the five cases are the same as the two extreme cases presented in the literature. In contrast, the other three cases investigated the structural behaviour of the frame in soft-storey and half-filled-storey systems. Based on the OMA analysis results, the natural frequencies, mode shapes and damping ratios of the frame system were extracted by the EFDD technique.

2. Formulation of the operational modal analysis technique

Using ambient excitations, the frequency response functions (FRFs) or impulse response functions (IRFs) cannot be easily obtained because the input force is not measured. Therefore, a modal identification method is required based on output-only data (Ren *et al*. 2004). There are several modal parameter identification techniques available in the literature.

The EFDD technique, which is an extension of the frequency domain decomposition (FDD) technique, was used in this study. In this technique, modes are simply chosen from singular value decomposition (SVD) plots calculated using the spectral density spectra of the responses. Because the FDD technique is based on using a single frequency line from a fast Fourier transform (FFT) analysis, the precision of the estimated natural frequency depends on the FFT resolution, and no modal damping is calculated in FDD. However, the EFDD technique provides an improved estimation of the natural frequencies and mode shapes, including the damping ratios (Jacobsen *et al*. 2006). In the EFDD technique, the single degree of freedom (SDOF) power spectral density (PSD) function, identified near a resonance peak, is reverted back to the time domain using the inverse discrete Fourier transform. The natural frequency is obtained by determining the number of zero crossings as a function of time and the damping by the logarithmic decrement in the corresponding SDOF normalized auto-correlation function (Jacobsen *et al*. 2006). In the FDD technique, the relationship between the unknown input $x(t)$ and the measured responses $y(t)$ can be expressed as the following (Bendat and Piersol 2010).

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

where $G_{xx}(j\omega)$ is the r×r PSD matrix of the input, r is the number of inputs, $G_{yy}(j\omega)$ is the m×m PSD matrix of the responses, m is the number of responses, H(jω) is the m×r FRF matrix, jω is the portion of the complex response and * and the superscript T denote the complex conjugate and transpose, respectively. The FRF matrix can be written as a partial fraction, i.e., in pole/residue form.

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

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

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

where s represents the singular values and the superscript H denotes the complex conjugate and transpose. Multiplying the two partial fraction factors and utilizing the Heaviside partial fraction theorem after mathematical manipulation, the output PSD can be reduced to the pole/residue form (Brincker *et al*. 2000).

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

where A_k is the 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 $\omega=\omega_i$ 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 the matrix $U_i=u_{i1},u_{i2},\ldots,u_{im}$, is the unitary matrix holding the singular vectors u_{ij} and S_i is the 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. The PSD function is identified by comparing the mode shape estimation u_{ij} with the singular vectors for the frequency lines near the peak. If a singular vector with a high modal assurance criterion value for u_{ij} is found, then the corresponding singular value belongs to the SDOF density function. From the component of the SDOF density function obtained near the PSD peak, the natural frequency and the damping values can be obtained (Brincker *et al*. 2000).

3. Experimental study

The produced RC frame system, base system and supporting details are depicted in Fig. 1. The experimental measurement system for determining the dynamic characteristics included uniaxial accelerometers, a 20-channel data acquisition unit (TESTBOX-6501) and the ambient response testing and modal identification software (ARTeMIS) platform (Structural Vibration Solutions 2013). Experimental measurements were carried out under ambient vibrations generated in the laboratory.

Fig. 1 Produced frame system

The test frame was produced as a ductile RC frame and properly designed according to the Turkish Seismic Code. During the design phase for the frames, a strong column-weak beam concept was taken into account. The dimensions and layout of the columns, beams and reinforcements for the first storey are shown in Fig. 2. The columns have approximately 1.5 times more moment bearing capacity than the beams with the selected dimensions. The columns were oriented along the 150 mm side in the out-of-plane direction. C25 concrete and S420 steel were used in the RC frame system. A concrete cover with a thickness of 5 mm was used. All the storeys of the frame system have the same properties as those of the first storey. The base system dimensions of the RC frame were 450×300 mm, and the frame was attached to the prepared rigid floor via holes drilled in the base system. The rigid floor is dimensioned to provide built-in support conditions. Horizontal hollow clay bricks (72×90×82 mm) were used as infill wall material. The picture of a typical brick used in this study can be seen in Fig. 3. The infill wall had an 82 mm thickness. For this purpose, the clay bricks were cut to have a scale 1/3 that of the local prototype bricks. Mortar with a thickness of 5 mm was used in the infill wall joints.

The experimental process was conducted on five models constructed on the RC frame system. The model details and the constructed models are shown in Table 1 and Fig. 4, respectively.

3.1 Material properties

3.1.1 Concrete

The concrete used for the frame system was prepared in the laboratory and developed by mixing fine aggregate, coarse aggregate, cement and water. The weight mixture ratios of the fine aggregate (0-7 mm), coarse aggregate (7-15 mm), cement and water were 28.9%, 149.2%, 13.3% and 8.6%, respectively.

To determine the compressive strength of the C25 concrete, 5 cubic specimens (150×150×150 mm) were acquired and left in a curing tank for 28 days. The cubic specimens were subjected to an axial pressure test using a

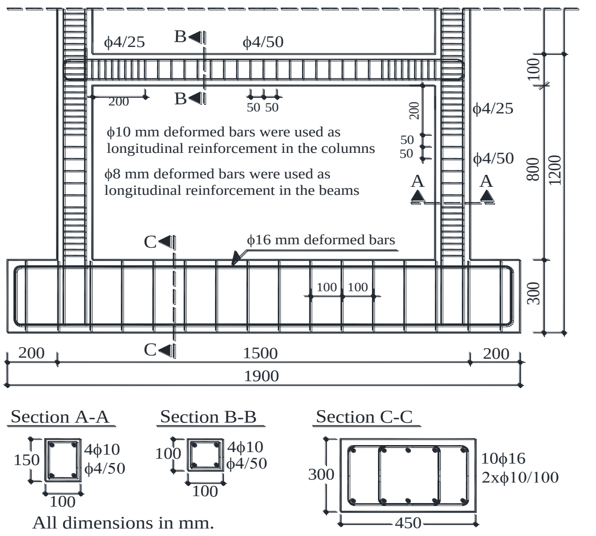


Fig. 2 Dimensions and layout of the columns, beams and reinforcements for the first storey

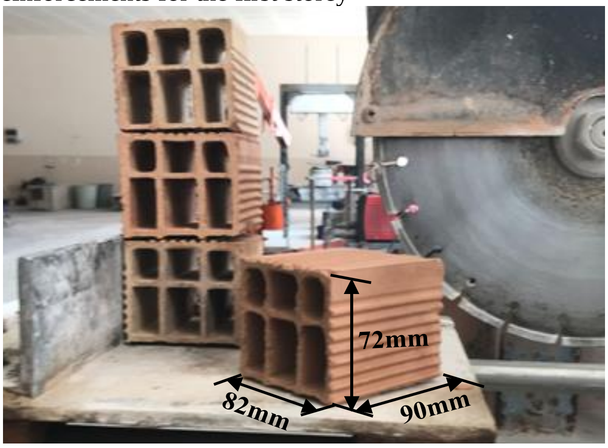


Fig. 3 A typical horizontal hollow clay brick used in this study

Table 1 Model details

Model No	Explanation
MODEL-I	No infill walls.
MODEL-II	The first and second storeys had no infill walls, and the third storey was fully filled.
MODEL-III	The first storey had no infill walls, and the other storeys were fully filled.
MODEL-IV	Half of the bay of the first storey was infilled, and the other storeys were fully filled.
MODEL-V	All storeys were fully filled.

loading device with a 2000 kN capacity. The 28-day average compressive strength of the concrete was calculated to be 33.04 MPa.

3.1.2 Steel

To determine the properties of the S420 steel bars used in the models, 3 steel specimens of each diameter were subjected to tensile tests by using a mechanical tensile testing device with a 200 kN capacity. In the beams and columns of the frame system, ϕ8- and ϕ10-diameter longitudinal steel bars and ϕ4-diameter stirrups were used,

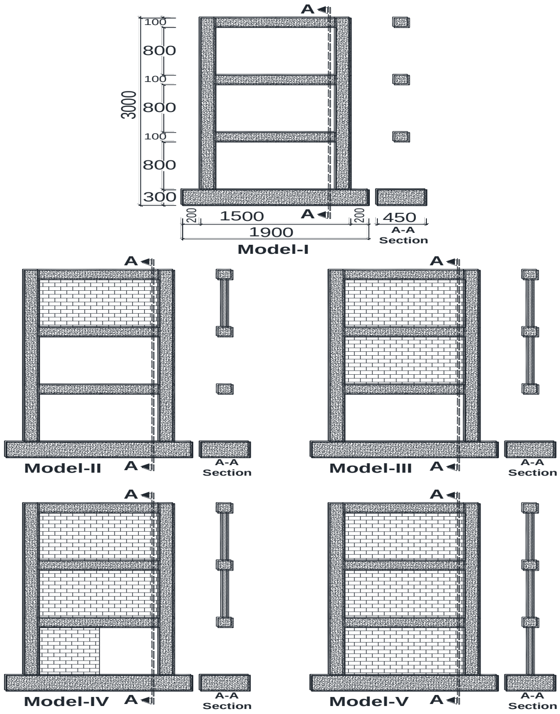


Fig. 4 Constructed models of the RC frame systems

respectively. The average yielding and ultimate stress values were 254 MPa and 381 MPa for ϕ4-diameter, 480 MPa and 600 MPa for ϕ8-diameter and 520 MPa and 620 MPa for ϕ10-diameter components, respectively.

3.1.3 Hollow clay bricks

Horizontal hollow clay bricks with sizes of 72×90×82 mm were used in the infill walls of the frame system. The uniaxial pressure tests were carried out parallel and perpendicular to the hollows to determine the compressive strength of the bricks. Average compressive strength values of 9.70 MPa and 6.37 MPa were recorded for the parallel and perpendicular directions, respectively.

3.1.4 Mortar

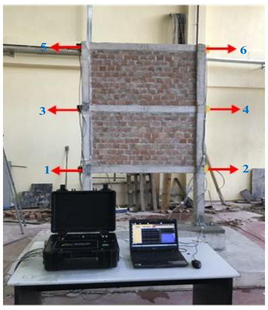
The mortar used for the infill wall masonry was prepared by mixing sand, cement, lime and water. The weight mixture ratios of the sand, cement, lime and water materials used in the mortar were 60%, 11%, 11% and 18%, respectively. Three cubic specimens (50×50×50 mm) were cast to determine the compressive strength of the mortar material. The specimens were subjected to a pressure test, and on average result of 4.05 MPa was the compressive strength value.

3.2 Measurements

The dynamic characteristics of the frame models including the frequency, mode shapes and damping ratios in the in-plane direction, were obtained by using 6 accelerometers. Twenty-minute records under ambient vibration were collected for each model, and the dynamic characteristics were determined using ARTeMIS (Structural Vibration Solutions 2013). The ambient vibrations,

Model-I

Model-II

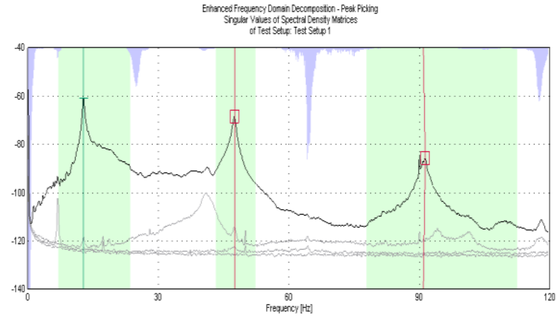


Model-III

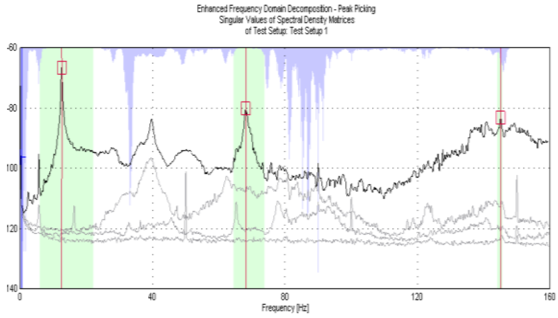
Model-IV

Model-V

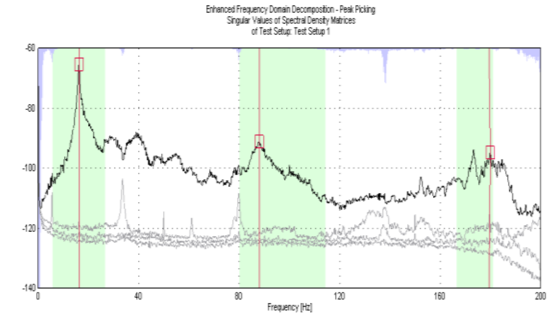
Fig. 5 The accelerometer locations



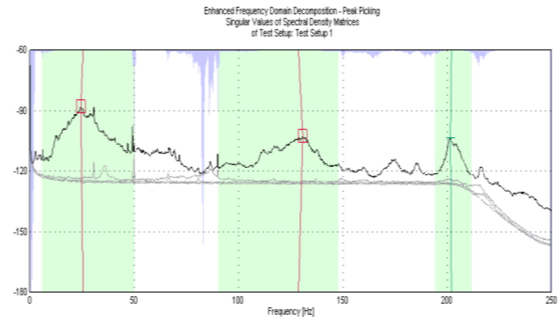
Model-I



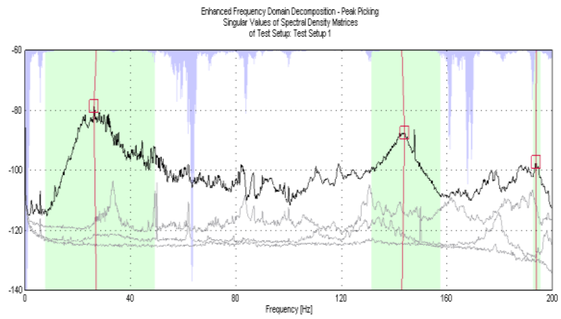
Model-II



Model-III



Model-IV



Model-V

Fig. 6 Singular values of the spectral density matrix for the models

generated by environmental excitations, were measured by seismic accelerometers fixed to the column-beam joints. The measured vibration signals were recorded via a 20-channel data logger unit (TESTBOX-6501). The accelerometer locations for the models are shown in Fig. 5.

The following points outline the work methodology:

1- Installing the sensors

2- Establishing the data collection unit and creating sensor connections

3- Recording ambient vibrations

4- Modelling the geometry using analysis software and inputting the recorded data

5- Determining the modal parameters

The data collected with the data logger unit for all the models were transferred to ARTeMIS (Structural Vibration Solutions 2013), and the dynamic characteristics of the structure were determined with the aid of the EFDD technique. The singular values of the spectral density matrix obtained using the EFDD technique in ARTeMIS (Structural Vibration Solutions 2013) are depicted in Fig. 6.

The frequency values and the modal damping ratios that belong to the in-plane direction modes were obtained from the singular values for the RC frame system, as given in Figs. 7-8.

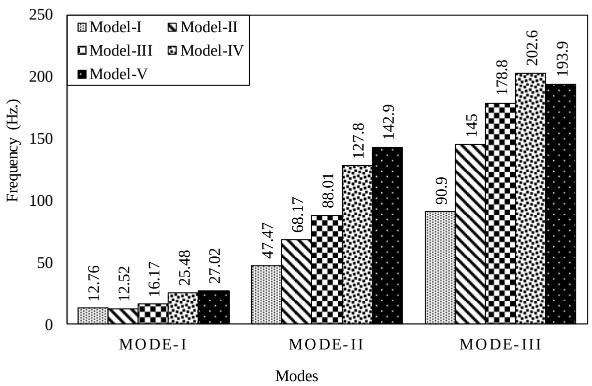


Fig. 7 Frequencies of the models for the three modes

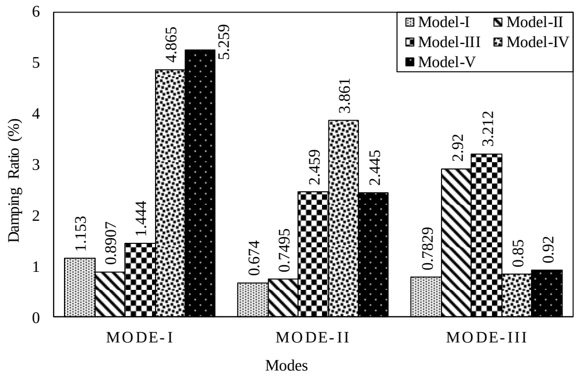


Fig. 8 Damping ratios (in %) of the models for the three modes

It is well known that during earthquake vibrations infill walls, though considered to be non-structural members, tend to significantly stiffen the structure through their strutting action. In most cases an analyst ignores this strutting effect of the infill wall while designing the building frame and only considers its mass thereby resulting in a more flexible structure (compared to the actual structure). In Fig. 7, while the amount of infill wall increased, the frequency values of the models increased for all modes. The increases in the frequency values of the first three modes for the fully infilled wall model were 111.76%, 201.03% and 113.31% of that of the bare frame model, respectively. Additionally, the increases in frequency in Model-III were 26.72%, 85.40% and 96.70% with reference to the bare frame model for the first three modes, respectively. This increase in frequency is caused by the contribution of the infill wall to the mass and stiffness of the RC frame. Considering the relationship between the frequency to the mass and stiffness, this increment occurred due to the evident contribution of the infill walls to the stiffness.

The damping ratios of the first three modes were obtained between 1.153-5.259%, 0.674-3.861% and 0.7829-3.212% for the models using the EFDD technique. Fig. 8 shows that, while the amount of infill wall increased, the damping ratio values of the models increased for all modes. The first three bending modes are illustrated in Fig. 9 for all models.

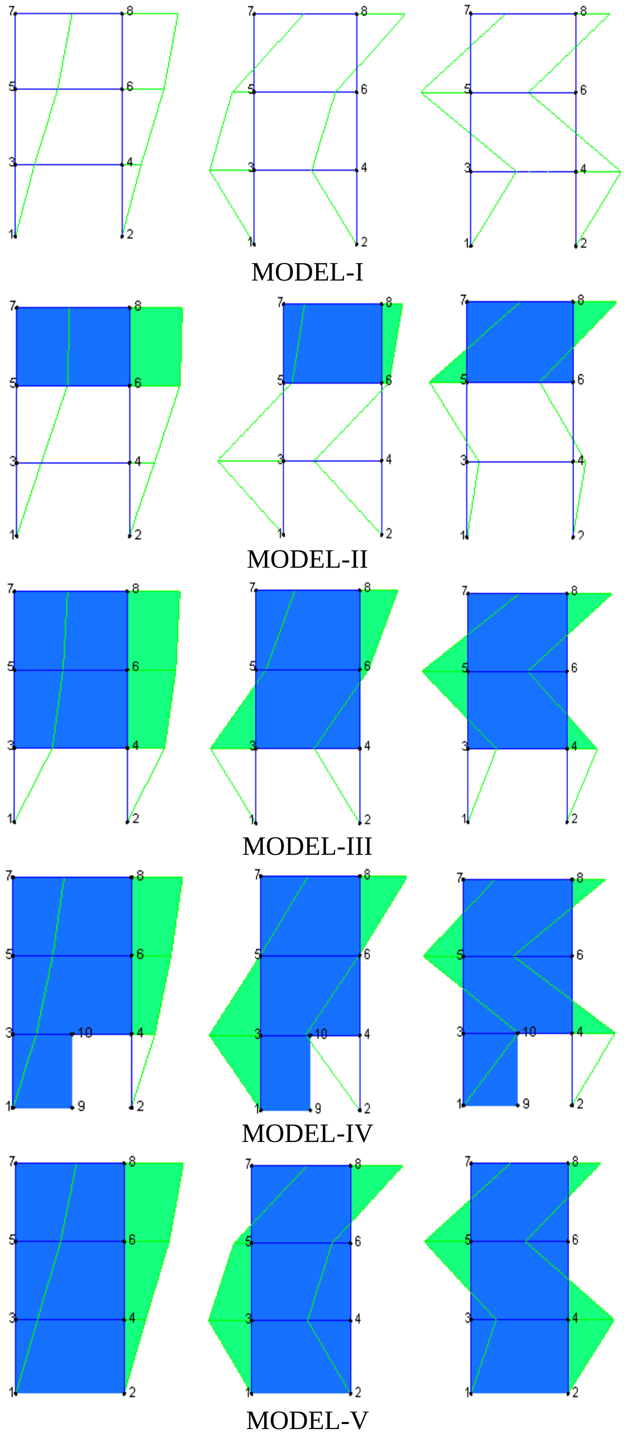


Fig. 9 Mode shapes of the models

As is well known, the frequency values increase either with increasing stiffness or decreasing mass. In our study, while the mass of the infilled model increases, the observed increment in the frequency values can be explained by the contribution of the infill wall to RC frame stiffness. The presence of infill walls in models considerably increased the stiffness and frequency values and changed the mode shapes. Thus, the dynamic behaviour of the RC reference frame system was quite different from that of the infill-walled RC frame system.

4. Conclusions

In this study, the dynamic characteristics including the natural frequencies, mode shapes and modal damping ratios of an RC frame system were investigated for various amounts of infill wall using OMA under ambient vibration conditions. For this purpose, a 1/3-scaled, single-bay, three-storey RC frame was produced. Experimental measurements were obtained for five different models. The produced models were Model-I (bare frame), Model II (the first and second storeys had no infill walls, and the third storey was fully filled), Model III (the first storey had no infill walls, and the other storeys were fully filled), Model IV (half of the bay at the first storey was infilled, and the other storeys were fully filled) and Model V (all the storeys were fully filled). Based on the experimental results of this study, the following conclusions can be made:

- The first three modes for all the models were determined to be the bending and lateral modes.
- When the first modes were compared, the frequency values and damping ratios increased with the effect of the infill walls. The increments in frequency were -1.88%, 26.72%, 99.68% and 111.76% for Model-II, Model-III, Model-IV and Model-V, respectively, compared to the bare frame model. Hence, the infill wall significantly increased the rigidity of the examined model.
- The damping ratios of the models produced using the EFDD technique were 1.153-5.259%, 0.674-3.861% and 0.7829-3.212% for Mode-I, Mode-II and Mode-III, respectively.

Consequently, infill walls significantly changed the dynamic behaviour of the RC frame system. This result showed that the effects of an infill wall should be considered for structural analysis. Finally, the results demonstrated that OMA is one of the important techniques for obtaining the current state of structures.

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