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RESEARCH ARTICLE

The effects of infill wall on dynamic characteristics of reinforced concrete frame systems

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Abstract

This study presents an experimental investigation on the dynamic characteristics of infilled Reinforced Concrete (RC) frames. For this purpose, a 1/3-scaled, one-bay, three-storey RC frame was produced and tested by using ambient vibration test. The experiments were performed on sequentially produced three specimens which use the same single reinforced frame. The infill walls were made of hollow clay brick. The frequency, mode shapes and damping ratios in the in-plane direction of patterns were obtained by six accelerometers. Fifteen-minute records under ambient vibration were taken for each model, and the dynamic characteristics were determined using the ambient response testing and modal identification software (ARTeMIS) program. The experiments showed that the infill walls significantly affected the frequency values and damping ratios of the frame system. As a result of this study, the presence of damaged/undamaged infill walls lead to an increase in the frequency values and the damping ratios for the first three modes of the frame systems. On the other hand, the natural frequency of the first three modes of with undamaged infill walls is more than those with damaged ones. While the damping ratios for undamaged infill walls were increased at first two modes and it was decreased at the third mode.

Keywords

Ambient vibration test; Reinforced concrete frame; Infill wall; Damage

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1. Introduction

The earthquakes occurred up to present showed that the majority of the buildings in Turkey have a weak seismic behavior. These are mainly due to insufficient material usage, architectural design faults, workmanship faults and insufficient usage of the stirrup bars and concrete class. These causes have adverse effects on the seismic performance of the buildings. It is extremely important to predict the problems that may arise and to take the necessary precautions. Operational modal analysis (OMA) is a very effective method to accomplish these purposes.

OMA has become a popular method in the last two decades. It is widely preferred in different engineering disciplines such as mechanical engineering, civil engineering and aerospace engineering. It has particularly been widely used to experimentally determine the dynamic characteristics of high-rise buildings, historical bridges and other structures. It is a non-destructive method based on the principle of the measuring the influences of ambient vibrations on the structure, which is used to determine the dynamic characteristics. In this method, environmental effects such as traffic, wave, wind, and tremors etc.

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are used as input. Due to some advantages of this method such as the determination of dynamic characteristics under actual service conditions, while not interrupting the use of structure during measurement, and being a quick and economic method, it is popularly used [1].

The dynamic characteristics of a structure might be determined by experimental and analytical methods. Since the analytical models that are made do not fully reflect the actual behavior of the building, real dynamic characteristics cannot be obtained due to the support conditions, the mass of structures and etc. To obtain more accurate results in analytical studies, researchers have made both experiments performed on full-scale constructions in the field and in experimental studies on scaled constructions in the laboratory conditions [2-9]. For this reason, experimental methods are needed to create a finite element model that will represent actual behavior.

In the design of the RC buildings, while the effects of the infill wall were applied as a load on the beams, the contribution to the stiffness is neglected. Therefore, the effects of infill wall on the dynamic characteristics are not fully represented. The experimental studies have shown that dynamic characteristics are significantly affected by infill wall [10-14]. For this reason, taking into account the infill wall effect in the analytical model will lead to a better representation of the behavior of the building.

In this study, the aim was to determine the effects of infill wall and damaged infill wall, which might be occurred by external effects on dynamic characteristics of the frame system. Therefore, one-bay, three-storey frame system was produced using different stages such as, bare frame, with infill wall and damaged infill wall and the OMA method were performed. In the experimental study, Enhanced Frequency Domain Decomposition (EFDD) was used to determine the dynamic characteristics.

2. Materials and methods

2.1. Operational modal analysis method

OMA is a non-destructive method to determine the dynamic characteristics of a structure such as modal shape, natural frequency, and damping ratio. In this method, the environmental effects such as traffic, wave, and tremors etc. are used as input.

OMA method is investigated under two phases which are time domain and frequency domain. While in the time domain decomposition method, the free response available at all time intervals is considered, in Frequency Domain Decomposition (FDD), a small frequency range in which a mode dominates in each mode is considered. Therefore, FDD method has an advantage of modal decomposition comparing with time domain decomposition [15].

FDD is an algorithm to identify the modal properties and it was first formulated by [16]. The EFDD technique is an extension of the Frequency Domain Decomposition (FDD) technique. The FDD technique is based on using a single frequency line from the fast Fourier transform analysis, the precision of the estimated natural frequency depends on the fast Fourier transform resolution, and no modal damping ratio is calculated in FDD. However, the EFDD technique provides an improved estimation of the natural frequencies and mode shapes including the damping ratios [17]. Also, the estimation of the modal shapes and natural frequencies is better by comparison with damping ratios in EFDD method. The estimation of the damping ratios was discussed, the new methods were compared with each other, and a method was proposed in order to get more reliable results in the damping ratio estimation [18].

2.2. Experimental study

In this study, a 1/3-scaled, one-bay, three-storey RC frame was produced and tested by using OMA. The experiments were performed on three specimens: one reference bare frame and two frames with infilled undamaged/damaged walls (Figs 1-3). The bay of the frame system was 1.4m and the height was 2.65m. The dimension of column was 10×15 cm and the dimension of the beam was 10×10 cm. In the beams and columns of the frame system, 4ϕ8 longitudinal steel bars and ϕ4-diameter stirrups were used. Stirrups were placed in central zone with 5 cm and in the confinement zone with 2.5 cm spaced evenly. The foundation of the frame system was considered as rigid and the foundation-column joint was designed as a fixed-support.

The concrete used for frame system was prepared in 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 materials in used concrete as 28.9%, 149.2%, 13.3% and 8.6%, respectively.

Fig. 1. Bare frame

Fig. 2. Frame with undamaged infill wall

a) General view

b) Detail view of damaged 1st storey

Fig. 3. Frame with damaged infill wall

To determine the compressive strength of C25 concrete, 5 cubic specimens (150×150×150 mm) were acquired and held in a curing tank for 28 days. The cube specimens were subjected to an axial pressure test using a 2000 kN capacity loading device. The 28-day average compressive strength of the concrete was calculated to be 33.04 MPa.

Horizontal hollow clay bricks with sizes of 72×90×82 mm was used in the infill walls of the frame system. The uniaxial pressure tests were carried out parallel and perpendicular to the hollows for determining the compressive strength of the bricks. The average results, 9.70 MPa and

6.37 MPa for parallel and perpendicular to the hollows, were obtained as compressive strength values, respectively.

The mortar used for the infill wall masonry was developed by mixing sand, cement, lime and water. The weight mixture ratios of the sand, cement, lime and water materials in used mortar as 60%, 11%, 11% and 18%, respectively. Three cubic specimens (50×50×50 mm) were employed to determine the compressive strength of the mortar material. The specimens were subjected to a pressure test and the obtained average result was 4.05 MPa as compressive strength value. Mixed mortar with a thickness of 5 mm was used in the infill wall joints. The first storey infill wall of the frame system was damaged by a jackhammer.

OMA was used for determining the dynamic characteristics as modal shape, natural frequency and damping ratio of three different patterns. The dynamic characteristics of the patterns in the in-plane direction were obtained by 6 pieces SENSEBOX7021 type accelerometers. The properties of accelerometers are given in Table 1. The ambient vibrations, generated by environmental excitations, were measured by seismic accelerometers fixed to the column-beam joints. Twenty-minute records under ambient vibration were taken for each model in the range of 0-250 Hz. The measured vibration signals were recorded via a 20-channel TESTBOX-6501 data logger unit and processed in the TESTLAB NETWORK software. Then, the dynamic characteristics were obtained by using EFDD method in ARTeMIS software [19].

Table 1. Technical Specifications of SENSEBOX7021 type accelerometer

Max. acc. measurement interval	±3g
Noise density	130ng/√Hz
Sensitivity	2400mV/g
Frequency interval	0-1200Hz
Shock resistance	2000g
Excitation voltage	±6-15VDC
Operating temperature	-55 – +65°C

3. Results and discussion

3.1. Determining modal parameters of bare frame system

To determine the dynamic characteristics of the bare frame system in the in-plane direction, 6 accelerometers were used which were fixed to the column-beam joints. Then, ARTEmIS software was used for analyzing the vibration data which were obtained from data acquisition unit. With this software, a model representing the frame system was created and vibration data were identified to the points by means of sensors. In the software, by use of EFDD, the spectral density matrix was obtained for first three modes (Fig. 4). In Fig. 4, the peak points represent vibration resonance of the structure and the frequency value of each resonance indicates the natural frequency of the structure. Using the frequency values of the peak points, the modal damping ratio of the building is obtained by different methods. The mode shapes that represent the modal behavior of the building are derived from the real parts of the function of each peak value [20].

Mod shapes, natural frequencies, and damping ratios obtained from experimental measurement of frame system are shown in Fig. 5.

3.2. Determining modal parameters of frame system with undamaged infill wall

In ARTEmIS software, by using EFDD method, spectral density matrix was obtained and shown in Fig. 6.

Modal shapes, natural frequency values and damping ratios which were obtained from experimental measurements shown in Fig. 7.

3.3. Determining modal parameters of frame system with damaged infill wall

The first storey of the infilled wall frame system was damaged in diagonal directions by using a jackhammer. The vibration data obtained with the help of accelerometers placed in this system were transferred to ARTEmIS software. The spectral density matrix was obtained by using of EFDD method and shown in Fig. 8.

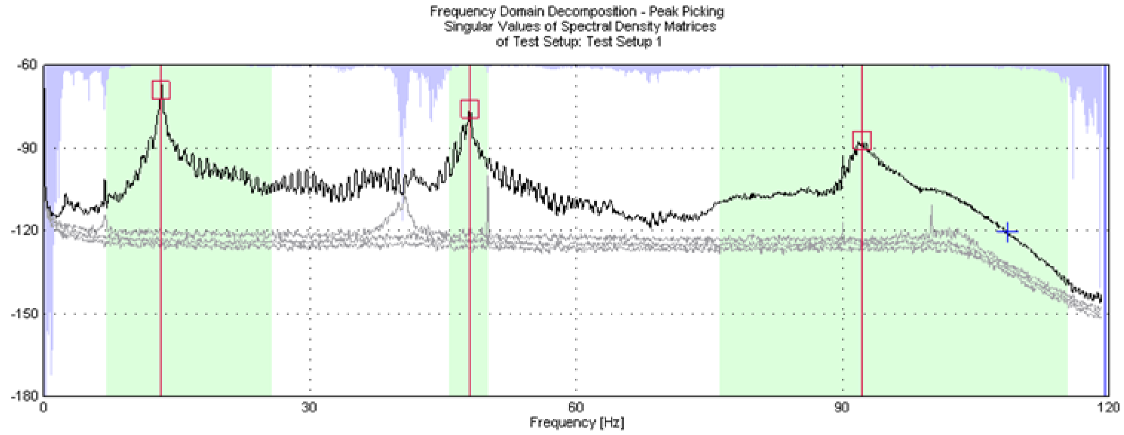
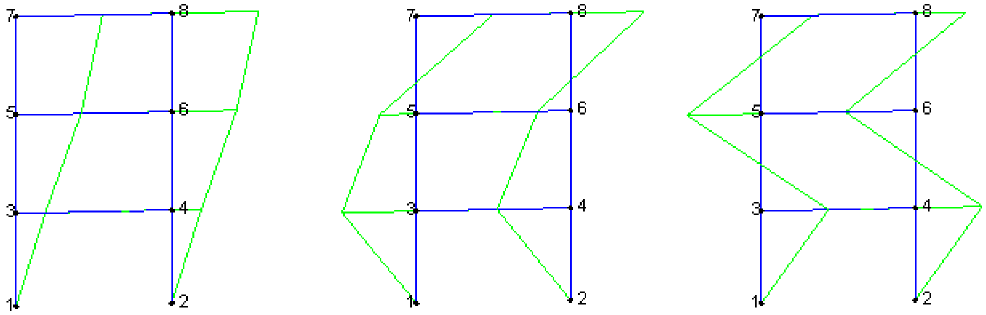


Fig. 4. Singular values of each modal shapes of bare frame system



f = 12.76 Hz ξ = 1.153 f = 47.47 Hz ξ = 0.674 f = 90.90 Hz ξ = 0.7829

Fig. 5 Modal shapes, frequency values and damping ratios of the frame system

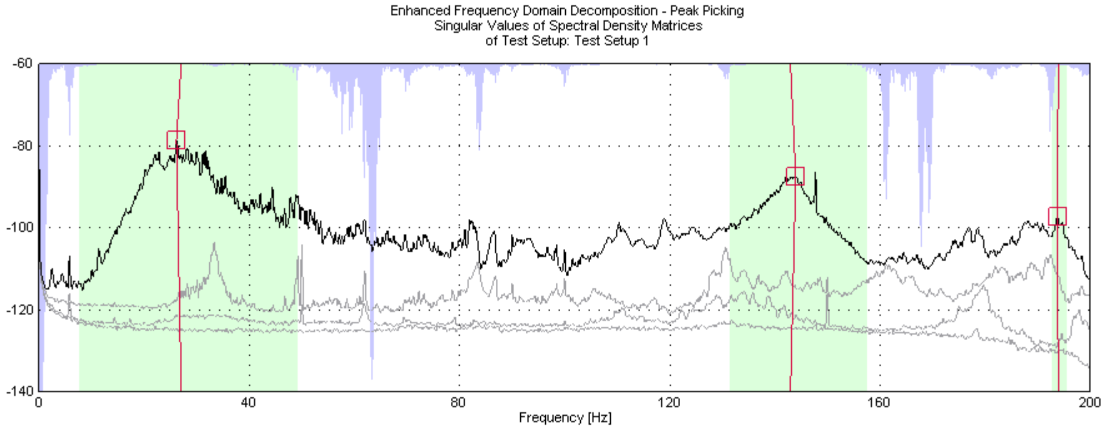
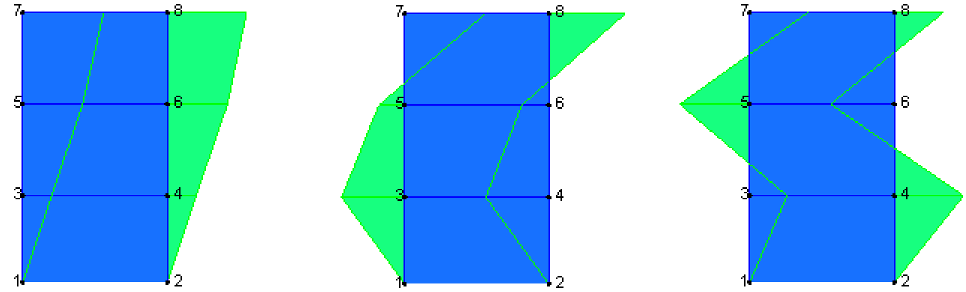


Fig. 6. Singular values of each modal shapes of the frame system with infill wall



f = 26.74 Hz ξ = 5.259 f = 142.7 Hz ξ = 2.445 f = 193.8 Hz ξ = 0.92

Fig. 7. Modal shapes, natural frequency values and damping ratios of undamaged frame system

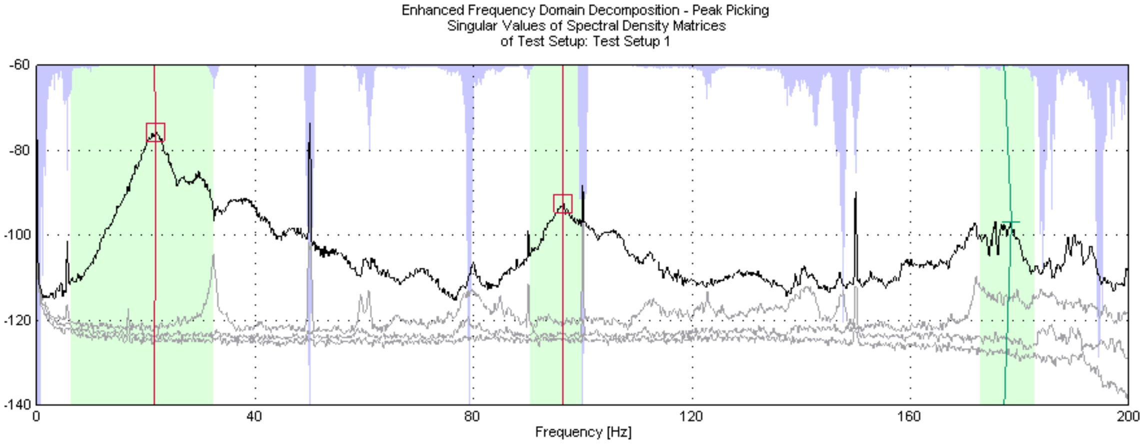
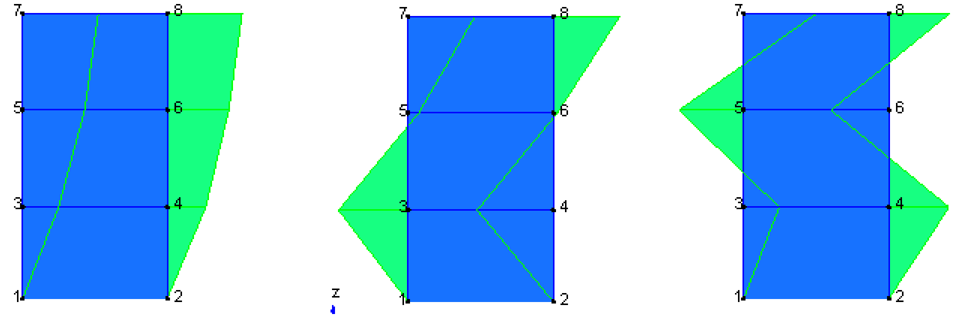


Fig. 8. Singular values of each modal shapes of frame system with damaged first storey infill wall

Modal shapes, natural frequencies and damping ratios of the damaged frame system obtained from the experimental measurements are shown in Fig. 9. Frequency values and damping ratios for the first three modes were summarized in Table 2.

The frequency values of the first three modes of the frame system with undamaged infill wall increased by %109.56, %200.61 and %113.2, respectively, compared to the frequency values of the bare frame system. Similarly, when the damping ratios were considered, the damping ratios of the frame system with undamaged infill wall increased compared to the bare frame system. On the other hand, frequency values of the frame system with damaged infill wall decreased by %20.08, %32.51, %8.62, respectively, compared to the undamaged condition.

When the damping ratios of the bare frame system and the infill wall frame system were compared, the damping ratios of the infill wall frame system increased in all three modes. The damping ratios of the first-floor infill wall damaged frame system with reference to undamaged infilled frame system wall ones were decreased in the first two modes and increased in the third mode. If the three measured models are compared, it can be said that the minimum damping ratios occurs in the bare frame system and the maximum damping ratios occurs in the undamaged infill wall case. Modal assurance criterion (MAC) was used to determine the relationship between mode shapes of the damaged and undamaged infill frame systems. According to the MAC values, given in Fig. 10 and Table 3, the second mode is the most sensitive to damage. On the other hand, the high correlation is obtained in the first mode.



f = 21.37 Hz ξ = 3.509 f = 96.31 Hz ξ = 1.787 f = 177.1 Hz ξ = 1.069

Fig. 9. Modal shapes, natural frequency values and damping ratios of damaged frame system

Table 2. Frequency values and damping ratios

Mode	Bare frame		With undamaged infill wall		With damaged infill wall	
	Frequency	Modal Damping Ratio	Frequency	Modal Damping Ratio	Frequency	Modal Damping Ratio
1	12.76	1.153	26.7	5.259	21.37	3.509
2	47.47	0.674	142.7	2.445	96.31	1.787
3	90.90	0.783	193.8	0.92	177.1	1.069

Table 3. MAC (Damaged and undamaged infill wall frame system)

Mode no		Undamaged		
		1	2	3
Damaged	1	0.991	0.032	0.025
	2	0.124	0.879	0.037
	3	0.085	0.128	0.935

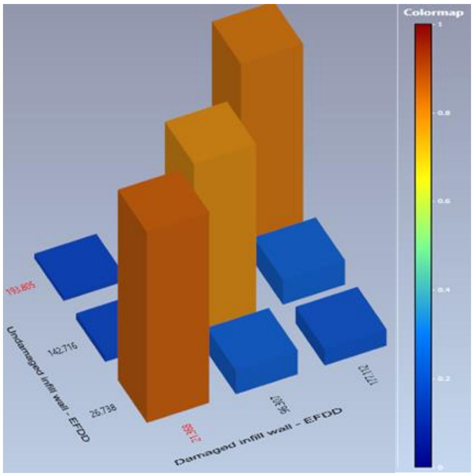


Fig. 10. MAC (Damaged and undamaged infill wall frame system)

4. Conclusions

In this study, the dynamic characteristics of a 1/3 scaled, one-bay, three-storey RC frame system were determined in three different conditions such as bare frame, with undamaged infill wall and damaged infill wall. The results of the study were presented below.

- The infill wall significantly increased the stiffness of the system, therefore for each three modes, natural frequency values and damping ratios increased.
- The damaged infill wall caused to decrease the stiffness. Consequently, the frequency values decreased compared with the undamaged condition. However, while the modal damping ratios decreased in the first two modes it increased in the third mode.
- It is understood that the infill wall significantly influences the dynamic characteristics of the frame system. Considering the infill walls in the analysis of the structures by the finite element method will also provide a more realistic representation of the behavior of the building.

- Modal assurance criterion (MAC) was used to determine the relationship between mode shapes of the damaged and undamaged infill wall frame systems. This criterion shows that the second mode shape is the most sensitive mode to damage.

Acknowledgements

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