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Theoretical and experimental dynamic characteristics of a RC building model for construction stages

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Abstract. Dynamic characteristics, named as natural frequencies, damping ratios and mode shapes, affect the dynamic behavior of buildings and they vary depending on the construction stages. It is aimed to present the effects of construction stages on the dynamic characteristics of reinforced concrete (RC) buildings considering theoretical and experimental investigations. For this purpose, a three-storey RC building model with a 1/2 scale was constructed in the laboratory of Civil Engineering Department at Karadeniz Technical University. The modal testing measurements were performed by using Operational Modal Analysis (OMA) method for the bare frame, brick walled and coated cases of the building model. Randomly generated loads by impact hammer were used to vibrate the building model; the responses were measured by uni-axial seismic accelerometers as acceleration. The building's modal parameters at these construction stages were extracted from the processed signals using the Enhanced Frequency Domain Decomposition (EFDD) technique. Also, the finite element models of each case were developed and modal analyses were performed. It was observed from the experimental and theoretical investigations that the natural frequencies of the building model varied depending on the construction stages considerably.

Keywords: construction stages; dynamic characteristics; finite element analysis; modal testing; operational modal analysis; reinforced concrete building

1. Introduction

Modal parameters such as frequencies, damping ratios and mode shapes affect dynamic behavior of buildings. These parameters are generally determined by discarding construction stage effects. However, they mainly depend on the storey mass and stiffness, which are influenced by the construction stages (Memari *et al*. 1999, Michel *et al.* 2008, Köse 2009, Bayraktar *et al*. 2010, Arslan and Durmuş 2013, Sevim *et al.* 2014).

The main construction stages of buildings can be classified into three cases: bare frame, brick-walled and coated. The bare frame cases consist of each level of frame system such as one-storey, two-storey, etc. The dynamic behavior of building type of structures can change during their construction stages. Especially, the brick walls cause a considerable effect on the modal behavior

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depending on the wall configuration. There are many studies on the construction stages of buildings for infill walls. Full-scale testing of a six-storey steel frame building with infill walls was performed by ambient and forced vibration methods (Memari *et al.* 1999). The dynamic responses for medium high-rise buildings were observed by Boroschek and Yanez (2000). The dynamic testing and stiffness evaluation of a six-storey timber framed building was presented by Ellis and Bougard (2001). Michel *et al.* (2008) investigated dynamic parameters of structures using ambient vibration measurements. The effects of building height, number of bays, ratio of area of shear walls to area of floor, ratio of infilled panels to total number of panels and type of frame on the fundamental period of RC buildings were investigated by Köse (2009). It has been presented the effect of construction stages to some extent in these studies. The identified dynamic characteristics were used for later assessment of building behavior by calibrating and updating analytical models (Brownjohn *et al.* 2001, Zonta *et al.* 2008). Also, damage identification algorithms have been developed by considering undamaged cases (Görl and Link 2003). Arslan and Durmuş (2013) were investigated the dynamic characteristics of RC frames for different construction stages (plane, brick in-filled and brick in-filled with plaster) by using OMA.

In the previous studies, construction stages for only infill walled or fully-completed buildings were presented by comparing natural frequencies and mode shapes. In this study, modal testing of a three storey reinforced concrete building model were performed for bare frame (one-storey, two-storey and three-storey cases), brick walled and coated stages. The modal parameters were determined for each construction stage of the scaled building model by Operational Modal Analysis method (OMA 2006) and Finite Element Analysis method (SAP2000 2008). The effects of construction stages were evaluated by considering the natural frequencies, mode shapes and modal damping ratios. Also, stiffness distributions for each stage were assessed by comparing modal behavior.

2. Modal testing

Modal testing is a form of vibration testing that determines the natural frequencies, modal damping ratios and mode shapes of structures. A modal testing procedure consists of two phases: acquisition and analysis. In the acquisition phase, the responses of the measured structure are acquired by sensors. The collected signals are analyzed to get modal parameters in the second phase. The modal testing method can be used for different purposes such as structural monitoring, structural identification, finite element model updating, damage detection, and so on. The modal testing methods are classified into two groups depending on the source of vibration used to vibrate the measured structures (Ewins 1995, Maia and Silva 1997). The first method is Experimental Modal Analysis (EMA) which uses known impact loads to vibrate structures and generally named as Forced Vibration Test (FVT). The second method is Operational Modal Analysis (OMA) which uses environmental vibrations and named as Ambient Vibration Test (AVT).

The most preferred method to modal testing is Operational Modal Analysis method because of usefulness and powerful. Modal parameters are identified from the measured signals by two common ways: Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI). The main relationship between the input and output signals in EFDD technique can be written as, where G_{xx} is the Power Spectral Density (PSD) matrix of the input signal, G_{yy} is the PSD matrix of the output signal, H is the Frequency Response Function (FRF) matrix, and * and T denote complex conjugate and transpose respectively.

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

The output PSD can be reduced to a residue form as follows (Brincker *et al.* 2000, Heylen *et al.* 2007)

$$\left[G_{yy}(\omega)\right] = \sum_{k=1}^{m}\left(\frac{[A_k]}{j\omega-\lambda_k} + \frac{[A_k]^{*}}{j\omega-\lambda_k^{*}} + \frac{[B_k]}{-j\omega-\lambda_k} + \frac{[B_k]^{*}}{-j\omega-\lambda_k^{*}}\right) \tag{2}$$

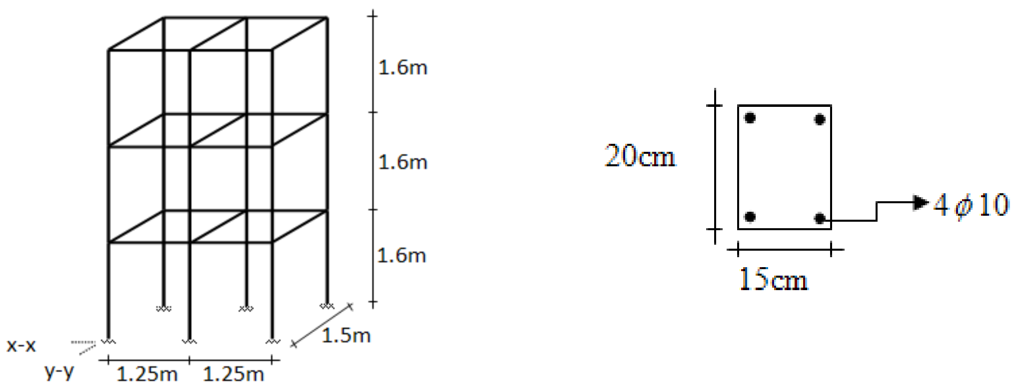
where A_k and B_k are the k-th residue matrices of the output PSD; λ_k is the pole.

3. Description of the RC building model

The model is designed to represent a typical three-storey RC building with a 1/2 scale. The total height of the building model is 4.8m. The length and width of the building model in the plan view are 2.5 m and 1.5 m, respectively. The building model is constructed on a rigid base slab with 50cm thickness. The dimensions of columns and beams are selected as 20×15 cm. The columns and beams have 3 cm^2 (4ϕ10) longitudinal bar area. The thickness of the each floor is 7.5 cm. The bars with 8 cm diameter are placed to the slab by 10 cm distance. A 3D view, dimensions and section properties of the RC building model are given in Fig. 1.

The classification of the concrete was C20, which has 20MPa compressive strength. Deformed reinforcement was used in the longitudinal and transverse directions. Vertically-cored brick were used in the walls. The thicknesses of the bricks were 19 cm and cement mortar were used in the interface between bricks and framing system.

The measurements were taken from each construction stages of the RC building model by nondestructive modal testing method and the dynamic characteristics (natural frequencies, mode shapes and modal damping ratios) were attained from the measurements. The study aims to present the modal parameters of a RC building model for main construction stages. The construction stages were considered as bare frame, brick-walled and coated cases. Also, bare frame was



(a) The dimensions of the model (b) The column and beam section

Fig. 1 The dimensions and section properties of the RC building model

(a) One-storey case

(b) Two-storey case

(c) Three-storey case

(d) Brick-walled case

(e) Coated case

Fig. 2 The construction stages of the RC building model

Fig. 3 A typical measurement setup on the RC building model

investigated in three sub-steps: one-storey, two-storey and three-storey cases. The construction stages can be seen in Fig. 2.

4. Modal testing of the RC building model for each construction stage

The experimental measurements were carried out by Operational Modal Analysis method. The tested models were vibrated by randomly generated impact loads. The impacts were applied to the base slab in different directions and amplitudes. The responses were measured by seismic accelerometers. The collected signals transferred into a portable computer via a data acquisition

Fig. 4 The accelerometer connection apparatus and accelerometer directions

Fig. 5 A typical measurement setup with reference signal

system. A typical measurement setup is given in Fig. 3.

Twelve uni-axial seismic accelerometers were used in each test. Frequency range and sensitivity of these accelerometers are 10000mV/g and 0.1-1500Hz, respectively. The accelerometers were placed to the corner and mid points of the each floor to get the responses in the longitudinal and transverse directions. The accelerometers were connected to steel apparatus which were anchored to each floor. The accelerometer connections and directions are shown in Fig. 4.

Since the accelerometer number and data acquisition system capacity were limited, the measurements on the two-storey and three-storey models were performed using reference signal. The data acquisition system enables to assign a reference signal to join the other signals from the sub-setups. So, the measurements on the RC building model were done with three sub-setups. The acceleration response on the mid-point of first store in the transverse direction was treated as the reference signal in all measurements. A typical measurement setup with reference signal is given in Fig. 5.

The frequency range was selected by performing pre-test to get the first five natural frequencies. Because randomly generated impact loads were applied to the tested models, the measurement duration was considered as five minutes. The power spectral densities for the tested model were attained by the EFDD technique after signal processing. The modal parameters of the RC building model were identified from these spectra.

4.1 Bare frame case

The first construction stage was considered as the bare frame system. This stage was taken into consideration as three sub-steps: one-storey, two-storey and three-storey cases. The dynamic

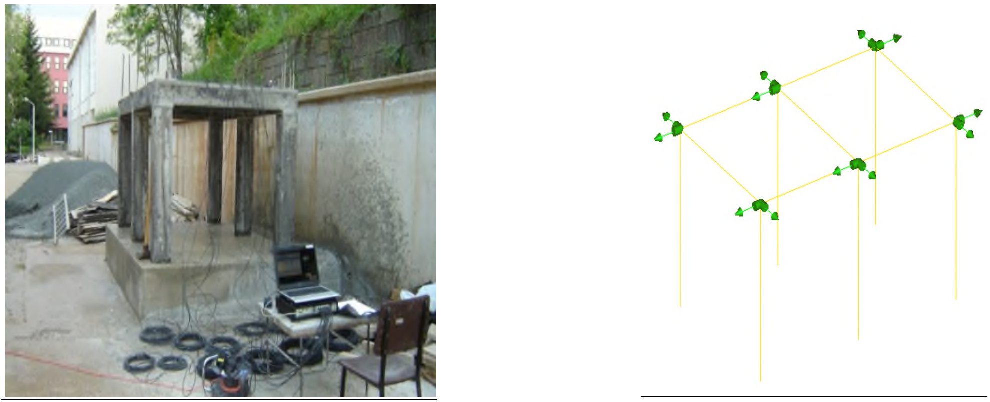


Fig. 6 The measurement setup on the one-storey building model

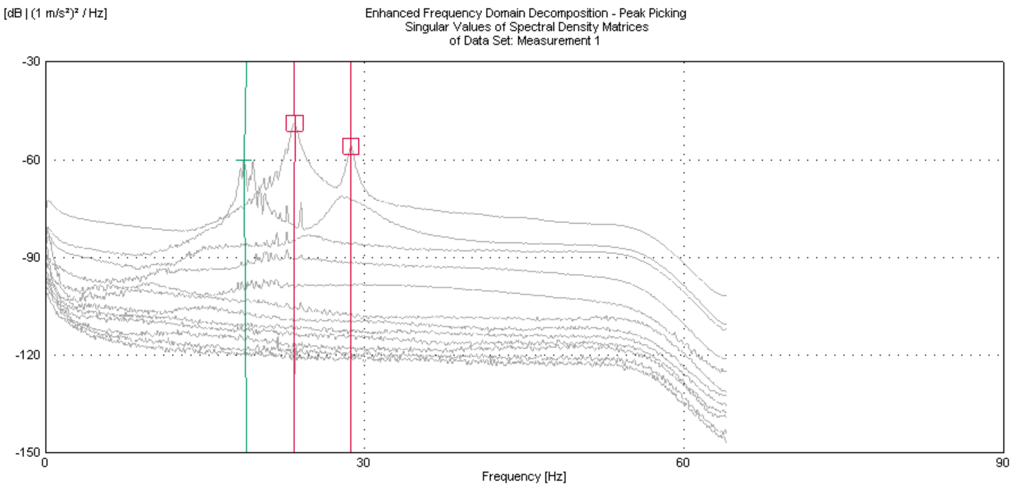


Fig. 7 The spectra of one-storey building model by EFDD technique

characteristics were determined for each stage. It was aimed that the dynamic behavior of the building model was stable during the measurements.

One-storey frame building

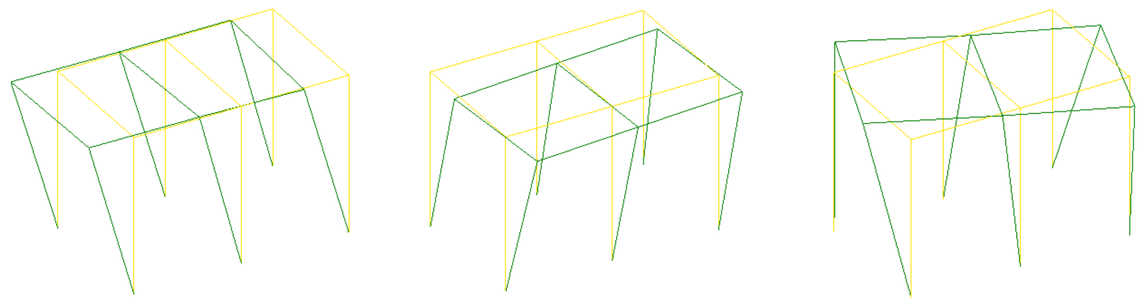
The measurement on the one storey frame building was performed with only one sub-setup. The frequency range for this measurement was selected as 0-50 Hz. The measurement setup and accelerometer directions are given in Fig. 6.

The spectra obtained by the EFDD technique for the one-storey case are presented in Fig. 7. The natural frequencies were selected by using Peak Picking method. Natural frequencies appeared as peaks on these spectra. After preliminary investigations of all response spectra, it was possible to determine the natural frequencies of the tested model.

The natural frequencies and corresponding modal damping ratios of the one-storey case are given in Table 1. In this table, all frequencies were divided into to the first frequency to show the coupling between natural frequencies apparently. The ratios (f_i/f_1) between the first three natural frequencies for the one-storey building model can be assumed well separated.

Table 1 The natural frequencies and modal damping ratios of the one-storey building model

Mode Number	Frequency (Hz)	Frequency Ratio (f_i/f_1)	Modal Damping Ratio (%)
1	18.91	1.000	3.345
2	23.40	1.237	1.381
3	28.72	1.519	1.044



1st longitudinal mode 1st transverse mode 1st torsional mode

Fig. 8 The first three mode shapes of the one-storey building model

Fig. 9 The measurement setup on the two-storey building model

The mode shapes were computed from the ratios of the peak amplitudes, taking into consideration the relative phase angle, at various points of the RC building model. The method assumes that the modes are real, and it provides good results if the modes are well separated. The mode shapes of the one-storey building model are shown in Fig. 8. The first three modal behaviors of this were the longitudinal, transverse and torsional modes, respectively.

Two-storey frame building

The measurement on the two-storey building was performed with two sub-setups using reference signal. The frequency range for this measurement was selected as 0-50 Hz. The measurement setup and accelerometer directions for this measurement are given in Fig. 9. The spectra for the two-storey case attained by the EFDD technique are given in Fig. 10.

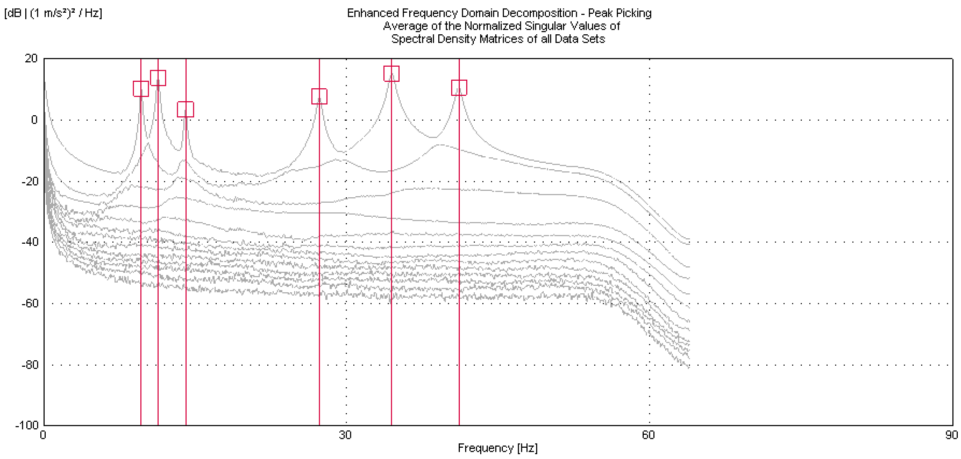
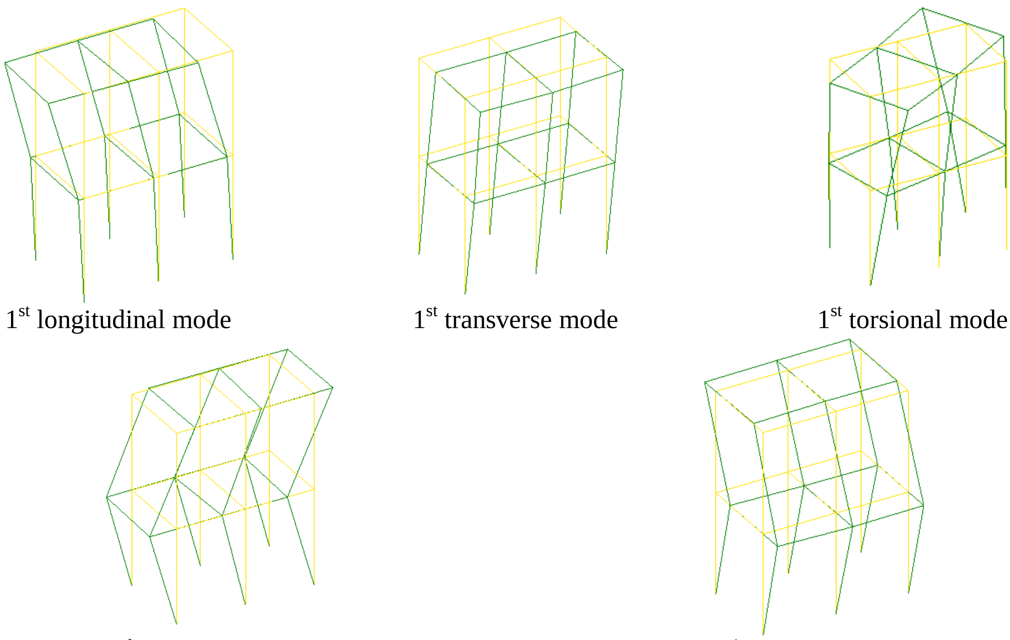


Fig. 10 The spectra of two-storey building model by EFDD technique

Table 2 The natural frequencies and modal damping ratios of two-storey building model

Mode Number	Frequency (Hz)	Frequency Ratio (f_i/f_1)	Modal Damping Ratio (%)
1	9.69	1.000	0.864
2	11.36	1.172	0.893
3	14.08	1.453	0.779
4	27.33	2.820	0.787
5	34.51	3.561	0.802



1st longitudinal mode 1st transverse mode 1st torsional mode

2nd longitudinal mode 2nd transverse mode

Fig. 11 The first five mode shapes of the two-storey building model

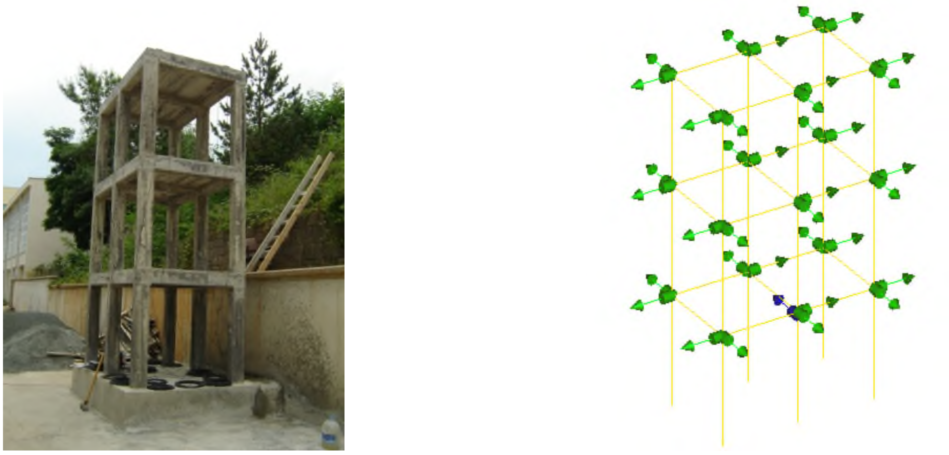


Fig. 12 The measurement setup on the three-storey building model

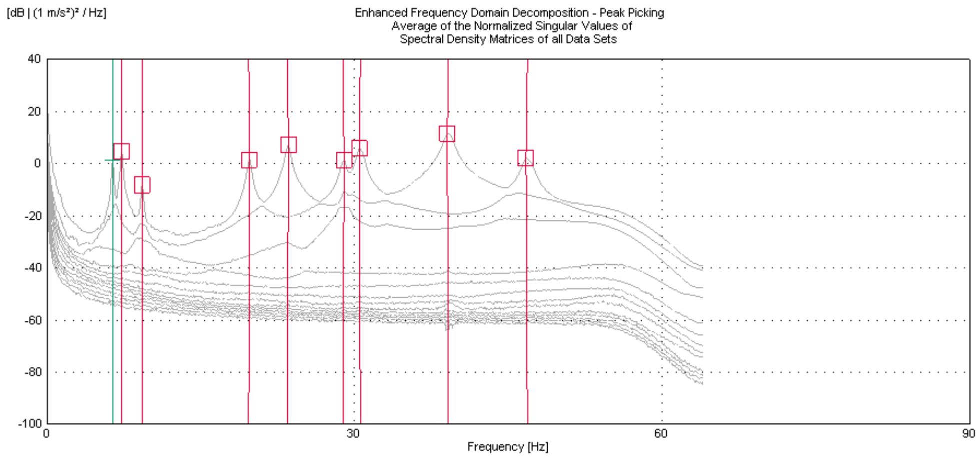


Fig. 13 The spectra of three-storey building model by EFDD technique

The first five natural frequencies and corresponding modal damping ratios of two-storey building model are given in Table 2. The ratios (f_i/f_1) between the first three natural frequencies can be assumed well. However, the frequency ratios for fourth and fifth modes are very high for this model. The fourth frequency is approximately three times higher than the first frequency.

The mode shapes of the two-storey building model are shown in Fig. 11. The first three modal behaviors of this model are also the longitudinal, transverse and torsional modes, respectively.

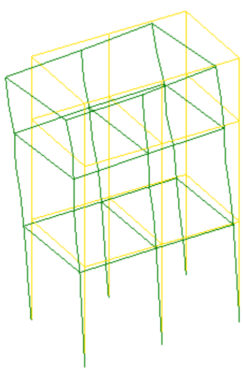
Three-storey frame building

The measurement on the three-storey building was performed with three sub-setups using reference signal. The frequency range for this measurement was selected as 0-50Hz. The measurement setup and accelerometer directions are given in Fig. 12.

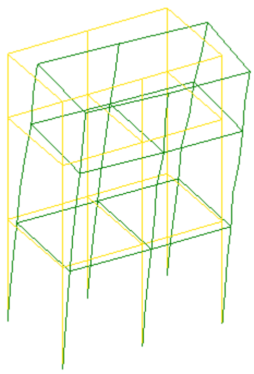
The spectra for the three-storey building model attained by the EFDD technique are shown in Fig. 13. The natural frequencies and corresponding modal damping ratios of this case are given in Table 3.

Table 3 The natural frequencies and modal damping ratios of three-storey building model

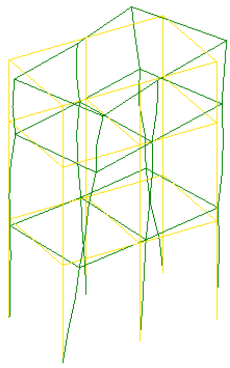
Mode Number	Frequency (Hz)	Frequency Ratio (f_i/f_1)	Modal Damping Ratio (%)
1	6.426	1.000	0.931
2	7.320	1.139	0.941
3	9.326	1.451	0.881
4	19.70	3.066	0.830
5	23.49	3.655	0.842



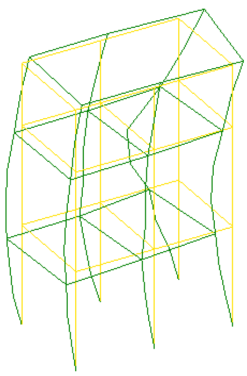
1st longitudinal mode



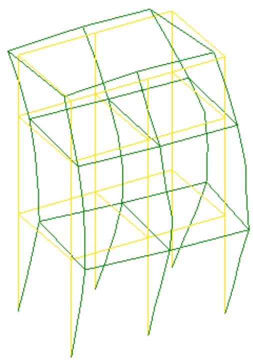
1st transverse mode



1st torsional mode



2nd longitudinal mode



2nd transverse mode

Fig. 14 The first five mode shapes of the three-storey building model

The first three frequencies have good frequency ratios. Also, the ratios got small by increasing store number. However, very high ratios for fourth and fifth modes occurred as in the two-storey case. The mode shapes of the three-storey case are shown in Fig. 14.

4.2 Brick-walled case

The second construction stage was considered as the brick walled case. In this case, it was applied brick walls with 19cm thickness to the whole model. There has not been just a wall of bricks in the front. The measurement on the walled building was performed with three sub-setups using

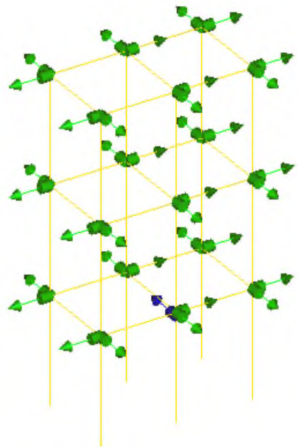



Fig. 15 The measurement on the brick-walled building model

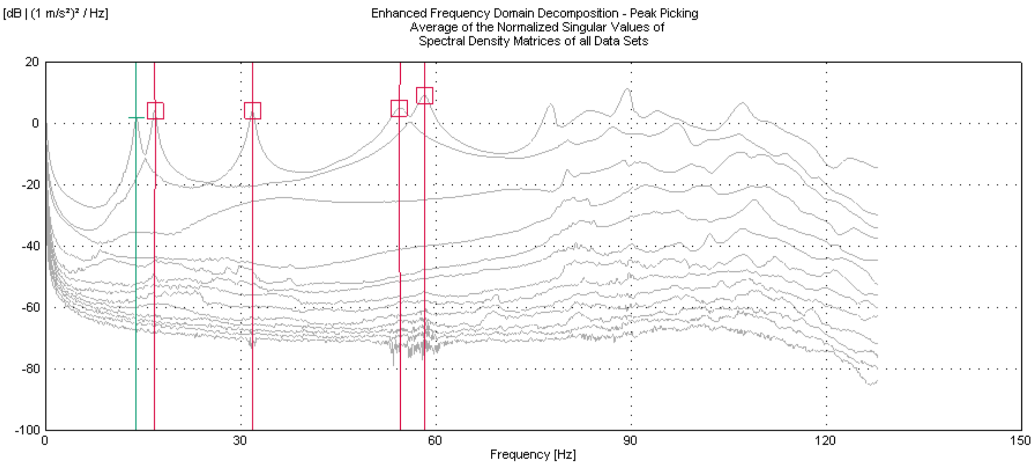
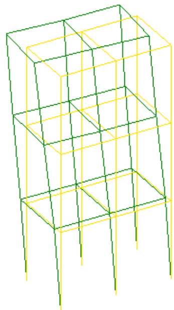


Fig. 16 The spectra of the brick-walled building model by EFDD technique

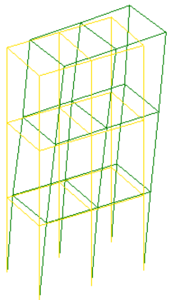
Table 4 The natural frequencies and modal damping ratios of the brick-walled case

Mode Number	Frequency (Hz)	Frequency Ratio (f_i/f_1)	Modal Damping Ratio (%)
1	11.18	1.000	1.611
2	13.17	1.178	1.202
3	20.67	1.849	1.008
4	37.76	3.377	2.016
5	44.35	3.967	2.147

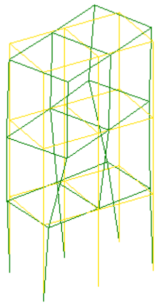
reference signal. The frequency range for this measurement was selected as 0-100 Hz because of the increase in the natural frequencies. The measurement setup and accelerometer directions for this case are presented in Fig. 15. The spectra for the brick-walled building model attained by the EFDD technique are given in Fig. 16.



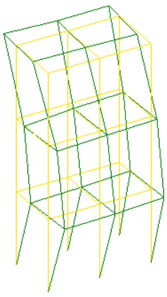
1st transverse mode



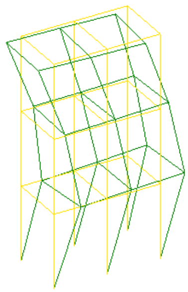
1st longitudinal mode



1st torsional mode



2nd transverse mode



2nd longitudinal mode

Fig. 17 The first five mode shapes of the brick-walled building model

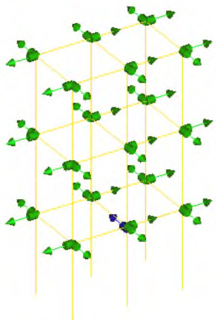


Fig. 18 The measurement on the coated building model

The first five natural frequencies and corresponding modal damping ratios of brick walled-building model are given in Table 4. The first two frequency ratios of the brick walled case are close to each other, but the third frequency is well separated in this case.

The mode shapes of the brick-walled model are shown in Fig. 17. The first three modal behaviors of the brick-walled model were the transverse, longitudinal and torsional modes, respectively.

4.3 Coated case

The third construction stage was considered as the coated case. In this case, the brick walled surfaces were covered with coating which have approximately 2 cm thickness. The measurement

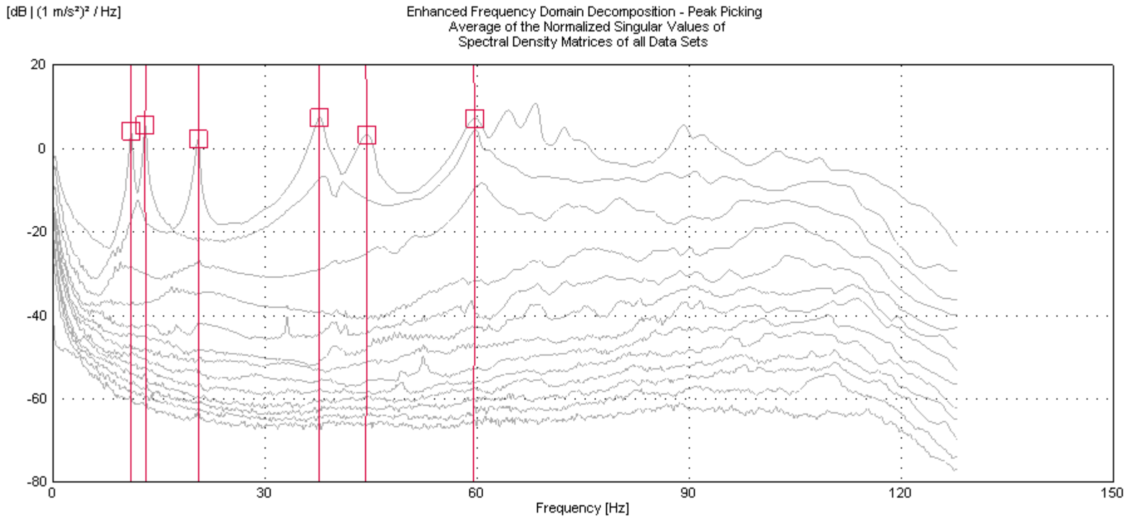


Fig. 19 The spectra of the coated building model by EFDD technique

Table 5 The natural frequencies and modal damping ratios of the coated building model

Mode Number	Frequency (Hz)	Frequency Ratio (f_i/f_1)	Modal Damping Ratio (%)
1	13.89	1.000	1.670
2	16.79	1.209	1.506
3	31.23	2.248	1.06
4	52.01	3.744	1.37
5	56.80	4.089	1.016

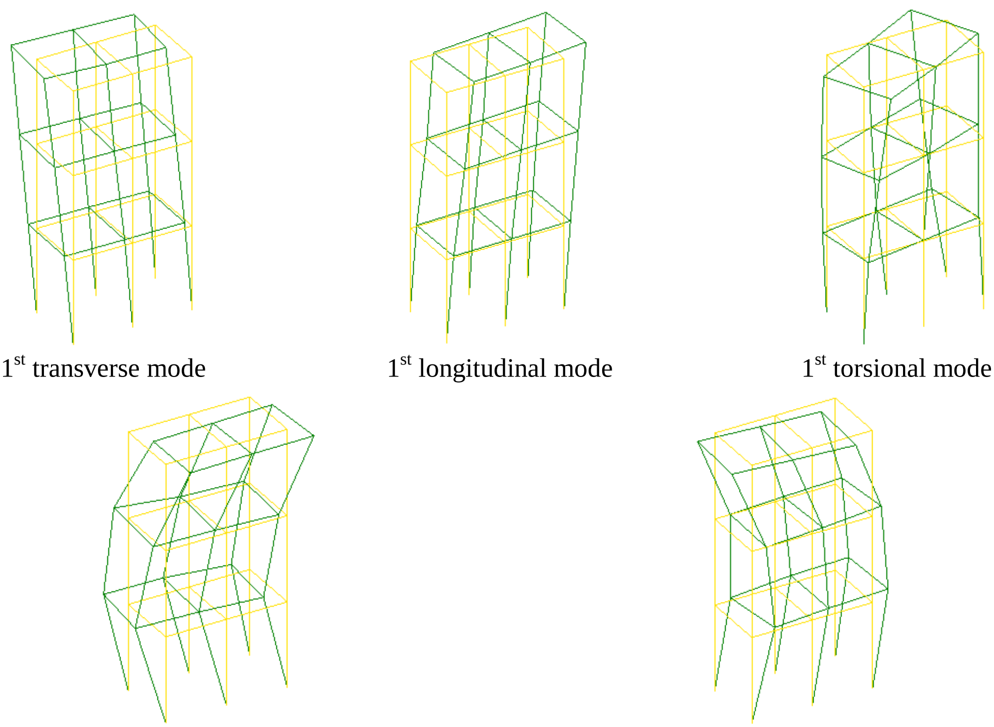
on the coated case was performed with three sub-setups using reference signal. The frequency range for this measurement was selected as 0-100 Hz. The measurement setup and accelerometer directions for this measurement are given in Fig. 18.

The spectra for the coated building model attained by the EFDD technique are given in Fig. 19. The natural frequencies and corresponding modal damping ratios of coated building model are given in Table 5. The coating cover creates an increasing effect on the separation between the first two frequencies and the third frequency.

The mode shapes of the coated building model are shown in Fig. 20. The first three modal behaviors of the coated building model were the transverse, longitudinal and torsional modes, respectively.

5. Theoretical analyses of the RC building model for each construction stage

The theoretical analyses were carried out by SAP2000 software (SAP2000 2008). Fame elements were used for beams and columns while area elements were used for slabs. There dimensional models for each case were created and modal analyses were performed. The first three dynamic characteristics were attained.



1^{st} transverse mode　　1^{st} longitudinal mode　　1^{st} torsional mode

2^{nd} transverse mode　　2^{nd} longitudinal mode

Fig. 20 The first five mode shapes of the coated building model.

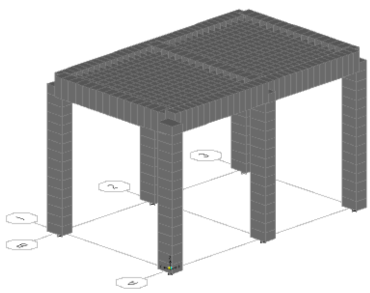
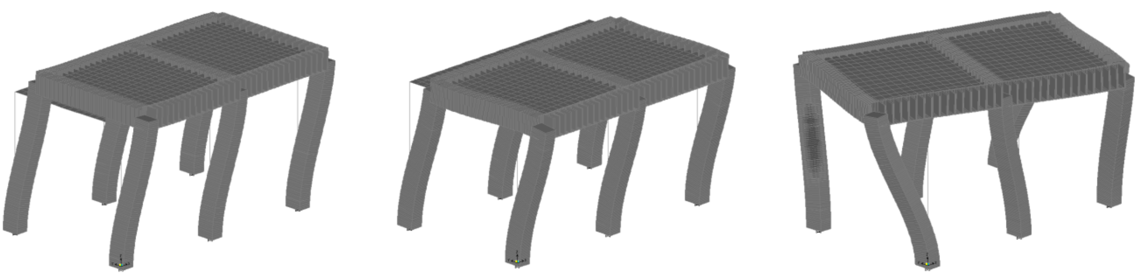


Fig. 21 The finite element model for one-storey building case



1^{st} longitudinal mode (19.941Hz)　　1^{st} transverse mode (24.645Hz)　　1^{st} torsional mode (30.309Hz)

Fig. 22 The first three mode shapes of the one-storey building model

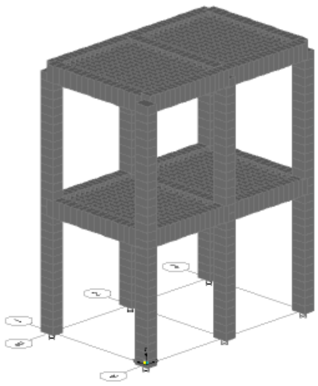
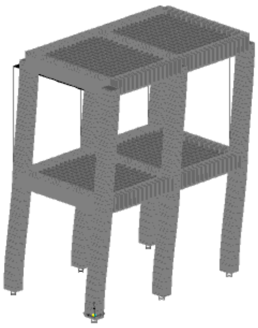


Fig. 23 The finite element model for two-storey building case



1st longitudinal mode
(10.205Hz)

1st transverse mode
(11.879Hz)

1st torsional mode
(14.762Hz)

2nd longitudinal mode
(29.089Hz)

2nd transverse mode
(36.563Hz)

Fig. 24 The first five mode shapes of the two-storey building model

One-storey frame building

The finite element model for this case was given in Fig. 21. The first three natural frequencies and mode shapes were given in Fig. 22.

Two-storey frame building

The finite element model for this case was given in Fig. 23. The first five natural frequencies and mode shapes were given in Fig. 24.

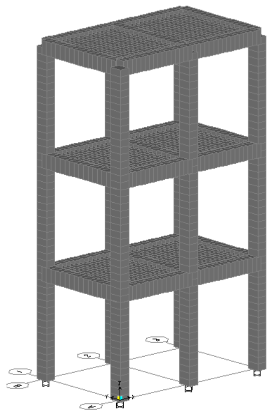


Fig. 25 The finite element model for two-storey building case

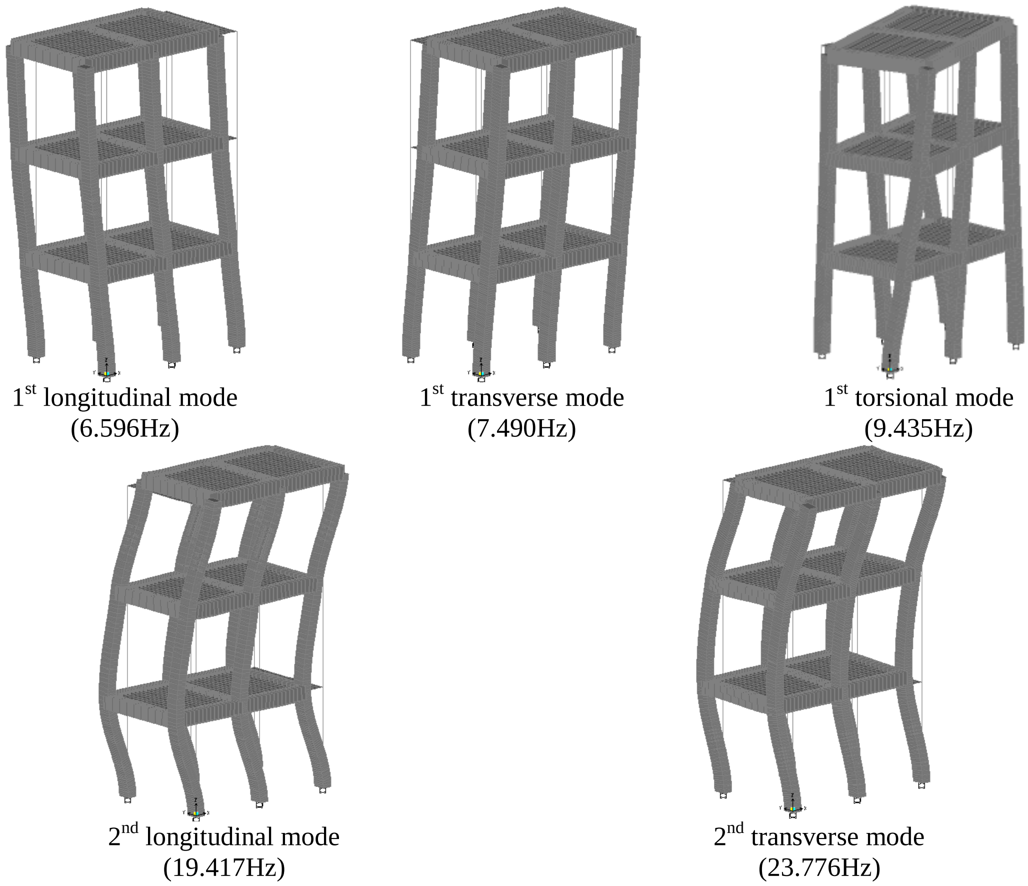


Fig. 26 The first five mode shapes of the three-storey building model

Three-storey frame building

The finite element model for this case was given in Fig. 25. The first five natural frequencies and mode shapes were given in Fig. 26.

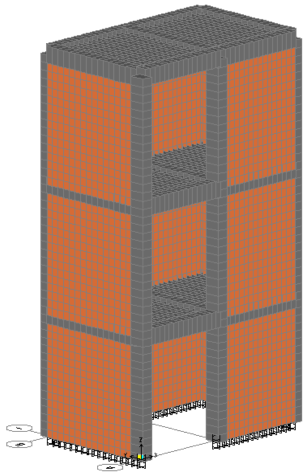
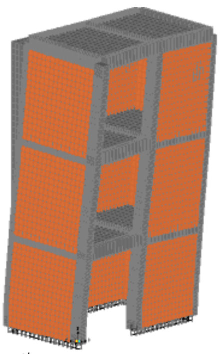
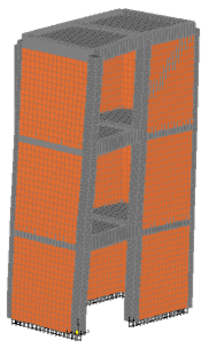


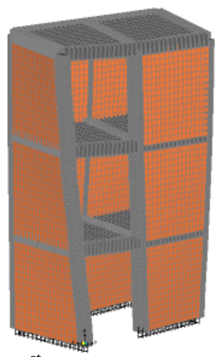
Fig. 27 The finite element model for brick-walled case



1st transverse mode
(13.074Hz)

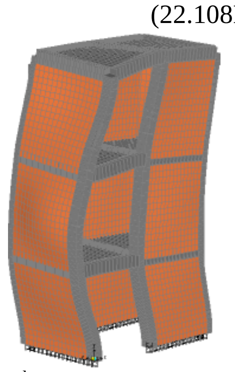


1st longitudinal mode
(14.601Hz)



1st torsional mode
(22.108Hz)

2nd transverse mode
(41.190Hz)



2nd longitudinal mode
(44.805Hz)

Fig. 28 The first five mode shapes of the building model for brick-walled case

Brick-walled case

The finite element model for this case was given in Fig. 27. The first five natural frequencies and mode shapes were given in Fig. 28.

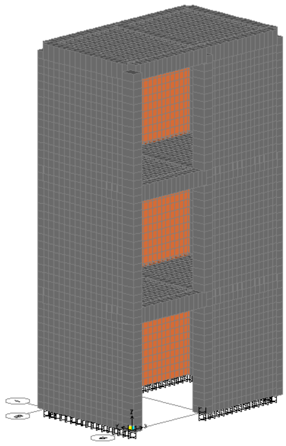
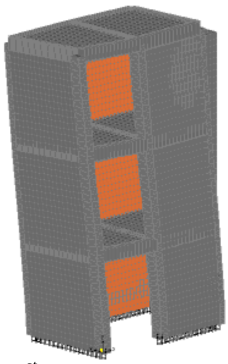
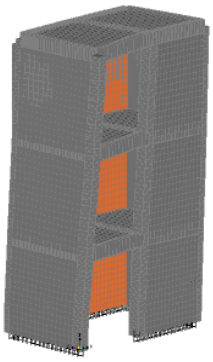


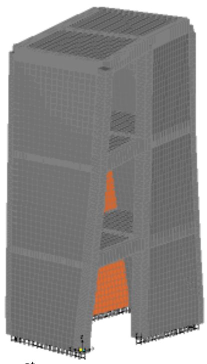
Fig. 29 The finite element model for coated case



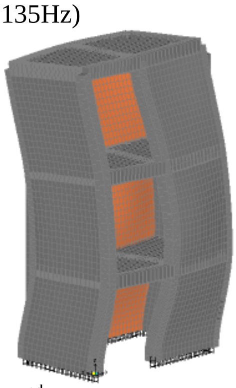
1st transverse mode (14.135Hz)



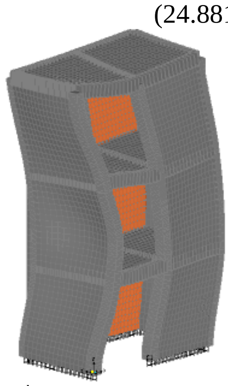
1st longitudinal mode (15.977Hz)



1st torsional mode (24.881Hz)



2nd transverse mode (46.110Hz)



2nd longitudinal mode (49.574Hz)

Fig. 30 The first five mode shapes of the building model for coated case

Coated case

The finite element model for this case was given in Fig. 29. The first five natural frequencies and mode shapes were given in Fig. 30.

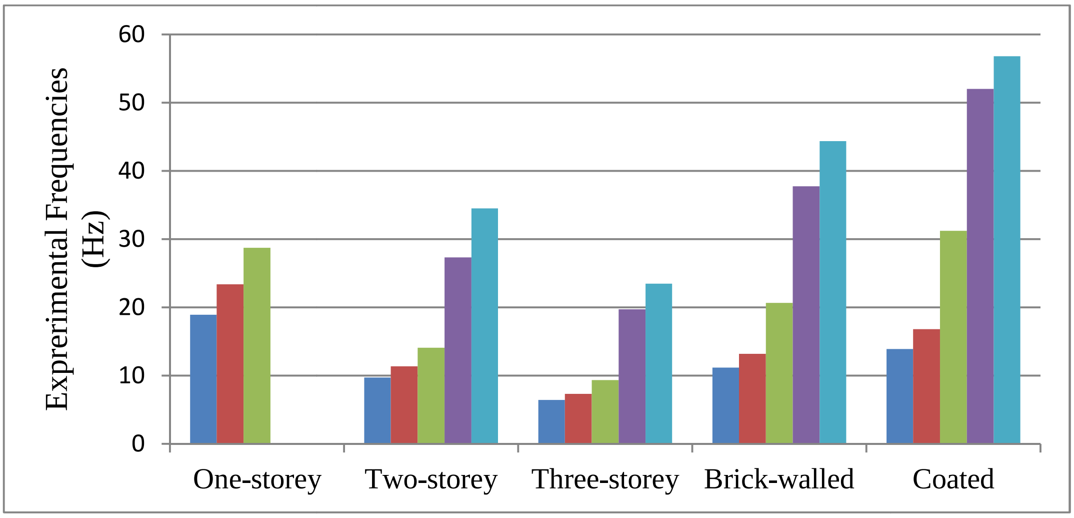


Fig. 31 The change in the natural frequencies for the each construction stage for experimental investigations

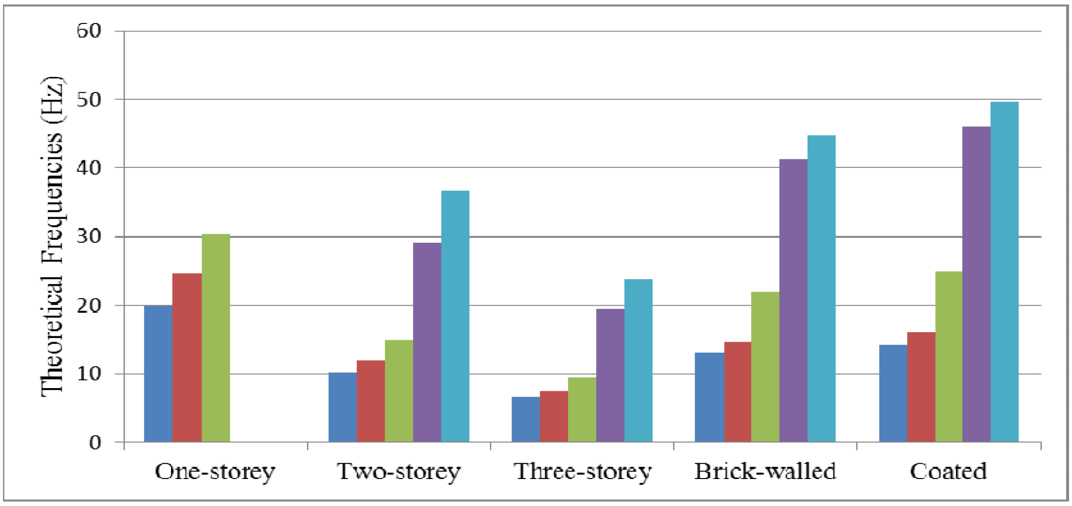


Fig. 32 The change in the natural frequencies for the each construction stage for theoretical investigations

6. Comparison of dynamic characteristics for construction stages

The natural frequencies of the building model varied depending on the construction stages. It was observed from the experimental and theoretical investigations that the natural frequencies decreased by increasing number of storey. The brick walls and coating also cause an increase in the natural frequencies. The changes in the natural frequencies for the each construction stages for experimental and theoretical investigations are presented in Figs. 31, 32, respectively.

It can be seen from Figs. 31 and 32 that the change in the natural frequencies are approximately the same in the first five modes for construction stages. The brick walls and coating cause a considerable increase in the frequencies. The effect is observed apparently in the third mode that the frequencies for coated case are three times higher than the bare frame case. The modal behavior is affected from the construction stages, especially from the brick walls. For the bare frame case, the mode shapes are the longitudinal, transverse and torsional, respectively; after the brick walls the modal behavior is changed as the transverse, longitudinal and torsional modes. This change demonstrate that the rigidity in the transverse direction considerably increased by the brick walls. The experimental and theoretical results are in a good harmony.

The ratio of third frequency to first frequency is 1.519 in the one-storey case, 1.453 in the two-storey case, 1.451 in the three-storey case, 1.849 in the brick-walled case, and 2.248 in the coated case for experimental investigations. These ratios were attained as 1.520 in the one-storey case, 1.446 in the two-storey case, 1.430 in the three-storey case, 1.690 in the brick-walled case, and 1.760 in the coated case for experimental investigations. The theoretical results were a bit bigger than the experimental results.

7. Conclusions

Dynamic characteristics, named as natural frequencies, damping ratios and mode shapes, affect the dynamic behavior of buildings and they vary depending on the construction stages. In this study, the effects of construction stages on the dynamic characteristics of reinforced concrete (RC) buildings were presented by considering theoretical and experimental investigations.

The experimental and theoretical investigations on the RC building model showed that the natural frequencies of the bare case decreased by increasing number of storey. Besides, the brick walls and coating created considerable stiffening effects on the building model and caused increases in the natural frequencies. The effect of brick walls and coating on the frequencies increased in the upper modes. The first three natural frequencies of the coated case were approximately two times higher than those of the bare case. The first three frequency ratios were generally close to each other for all construction stages, but the fourth and fifth frequency ratios were well separated. The coupling between the first three modes decreased in the construction of stories.

The ratio of third frequency to first frequency is 1.519 in the one-storey case, 1.453 in the two-storey case, 1.451 in the three-storey case, 1.849 in the brick-walled case, and 2.248 in the coated case for experimental investigations. These ratios were attained as 1.520 in the one-storey case, 1.446 in the two-storey case, 1.430 in the three-storey case, 1.690 in the brick-walled case, and 1.760 in the coated case for experimental investigations. The experimental and theoretical results are in a good harmony. The theoretical results were a bit bigger than the experimental results.

From the experimental investigations, the modal damping ratios for the bare cases decreased by increasing number of storey while they increased for the brick-walled and coated cases. The modal behavior of the RC building model changed depending on the construction stages. The brick walls affected the rigidity distribution of the building model. The rigidity in the transverse direction increased much more than the longitudinal direction for this wall configuration. So, the first mode occurred in the transverse direction for the brick-walled case.

Acknowledgements

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