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Calibration of FE models of reinforced concrete specimens using experimental modal analysis

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Abstract. In modern engineering practices, finite element models of structures are generated using specialized structural analysis software, and simulations are conducted in computational environments. To ensure that these analyses accurately represent the actual structural behavior and produce realistic results, finite element models are calibrated using dynamic properties obtained from experimental modal analysis. In this study, five small-scale two storey one bay reinforced concrete specimens tested. Theoretical modal analysis results were obtained for these specimens using the SAP2000 software. Concurrently, the reinforced concrete specimens were excited using an impact hammer (modal hammer), and their dynamic responses were recorded using uniaxial accelerometers installed at specific floor levels. The force and acceleration signals collected during the experiments were processed in the frequency domain using dedicated signal processing software to derive transfer functions for the reinforced concrete models subjected to impact excitation. Through these analyses, the dynamic properties of the structures, including mode shapes, natural frequencies, and damping ratios, were determined. Then, the experimental modal analysis results for each reinforced concrete specimen were compared with the theoretical modal analysis results of the SAP2000 finite element model calibrated with the modulus of elasticity variation. Calibrating the analytical model with the experimental modal analysis results increases the reliability of the finite element model. This approach contributes significantly to accurately predicting structural behavior and provides a robust basis for more precise finite element modeling in future structural engineering research.

Keywords: Experimental modal analysis; Modal hammer; Finite element model; RC specimens

1. Introduction

In structural engineering, accurately predicting the behavior of designed systems under various external forces forms the basis of safe and functional designs (Chopra, 2017). In addition to static loads, dynamic loads—such as earthquakes, wind, traffic, or machine vibrations—have been shown to influence the response of structures significantly. These dynamic interactions are directly related to the fundamental properties of structures, such as mass and stiffness, and can lead to undesirable consequences like resonance, excessive oscillation, and structural damage.

At this stage, Modal Analysis is a critical method. This discipline, which involves the determination of a structure's vibratory properties through either experimental investigation or analytical modeling, facilitates the comprehension of structural dynamic behavior by characterizing its natural frequencies, damping ratios, and mode shapes (Ewins, 2000). Knowing these vibration properties is crucial for predicting and improving how structures respond to different dynamic forces.

Modal analysis is a methodology widely applied in various engineering disciplines. It is used in various fields such as civil engineering, automotive engineering, aeronautical engineering, astronautical engineering, electronics, and sports equipment design. The material properties specific to structures in these various engineering branches, combined with the variability of the environmental conditions to which they are exposed, often require various measurement techniques and data processing strategies.

Operational Modal Analysis (OMA) and Experimental Modal Analysis (EMA) represent two primary methodologies for identifying the dynamic properties of structures, which are fundamentally different from these models by the treatment of input excitation. OMA takes advantage of naturally occurring ambient or operational forces acting on a structure, where these input forces are not directly measured; the analysis focuses only on the

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structural response. In contrast, EMA involves the application of a known and measurable input force to the structure, typically using instruments like modal hammers or shakers, allowing for direct input-output characterization of the system's dynamic behavior. This difference in input force measurement forms the core distinction between these two widely applied techniques in structural dynamics.

The practical difficulties of using impact hammers can make EMA challenging, especially when studying large structures. For this reason, OMA is often a more practical and effective method for understanding the dynamics of large-scale systems (Grosel et al., 2014). However, when analyzing smaller structures, both EMA and OMA have been shown to produce similar and reliable results.

Nowadays, EMA, especially when applied to impact testing, is a frequently used and preferred method for determining the vibration characteristics of structures. EMA has been widely accepted due to its advantages, such as low uncertainty in the applied force, a better understanding of the test conditions, easy applicability, fast results, and economy (Schwarz & Richardson, 1999; Zoltowski & Napieraj, 2017).

In current engineering design processes, finite element (FE) software is common, often relying on certain assumptions. The economic benefits of FE analysis frequently lead to its selection over physical experiments. However, it is important to recognize that real-world structural behavior may differ from theoretical predictions. Therefore, a reliable way to improve the validity and accuracy of FE analysis assumptions is to compare the outcomes of experimental studies with those from FE simulations. Many research projects have assessed the effectiveness of EMA on different structural materials and systems and how well its results align with analytical findings.

Prasad and Seshu (2008) conducted an experimental modal analysis on beams of different materials using an impact hammer. In their study, they compared their experimental results with theoretical analyses and FE software analysis results. Similarly, a study by Walunj et al. (2015) investigated the modal parameters of cantilever beams using the experimental modal analysis method. Sharma (2019) also presented a comparative study of theoretical and experimental modal analysis on beams.

Chandravanshi and Mukhopadhyay (2013) investigated the dynamic characteristics (frequency, mode shape, damping) of a two-story steel structure using experimental modal analysis. They then analyzed the same structure using the finite element method with the ANSYS program and subsequently compared the results obtained from the experimental and numerical approaches.

Bayraktar et al. (2010) experimentally obtained and investigated the dynamic parameters of three reinforced concrete buildings at different construction stages. Altunisik et al. (2013) applied analytical and experimental modal analyses to determine the dynamic characteristics of a scaled bridge model.

Arslan and Durmus (2014) conducted OMA experiments on single-story reinforced concrete frames to investigate the role of infill walls on the dynamic response of structures. These experiments tested both bare frames and frames with brick infill walls. A finite element model was also created and calibrated using the SAP2000 program.

Orlowitz and Brandt (2017) conducted a detailed comparison of EMA and OMA using a laboratory-tested plate. Their study aimed to evaluate the effectiveness and applicability of both methods under controlled conditions. The research examined the accuracy of identified dynamic properties and the practical aspects of each technique. This work provides knowledge of the relative merits of EMA and OMA for structural analysis.

Azmi et al. (2021) conducted an experimental modal analysis on a two-story reinforced concrete frame. In this study, they determined the structure's natural frequencies using impact testing and accelerometers. They compared the experimental results with the results from a finite element model they created using the HYPERWORK program. The findings showed that the natural frequencies measured experimentally were in significant agreement with those obtained through numerical modeling.

Filippoupolitis and Hopkins (2021) conducted a study investigating the dynamic behavior of damaged reinforced concrete beams. In their research, they utilized EMA to understand the effects of structural discontinuities on the vibration characteristics of these beams. Additionally, they employed Finite Element Methods (FEM) to support their experimental findings with numerical modeling.

In a study by Ahmed and Mohammad (2015), the EMA method was employed to understand the dynamic characteristics of reinforced concrete square plates. These researchers determined the plates' natural frequencies and mode shapes through experiments performed in a laboratory setting.

Sevim et al. (2011) collected experimental data on the dynamic properties of two historical arch bridges using ambient vibration tests, and they calibrated the finite element models created in the ANSYS program using this data. Günaydin et al. (2017) initially performed an analytical determination of the modal parameters of the reinforced concrete buildings constructed under laboratory conditions, employing the ANSYS software. Subsequently, they conducted ambient vibration tests to experimentally validate these parameters, utilizing the acquired data to refine the initial finite element models for increased accuracy.

Altunisik et al. (2024) updated the finite element models of the historical Santa Maria Church and its Guesthouse in Trabzon using the dynamic properties obtained from a non-destructive experimental investigation with ambient vibration testing.

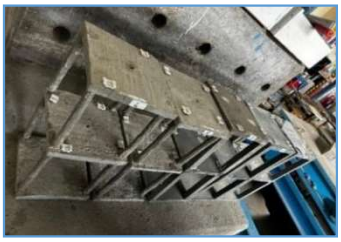
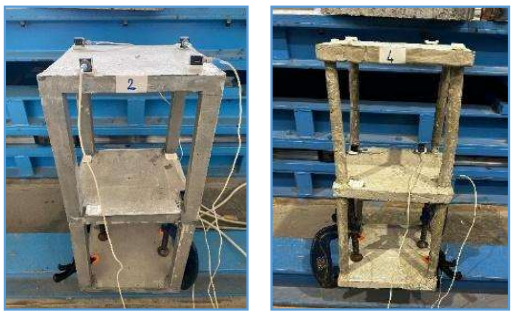


Fig. 1. RC specimens

In this study, experimental modal analysis was performed on five reinforced concrete frame structures, as presented in Fig. 1. Using an impact hammer as an exciter, the natural vibration frequencies and corresponding mode shapes, which are the basic dynamic characteristics of the structures, were determined. In addition, the modal analysis of the same structural configurations was carried out analytically using SAP2000 software. A calibration process was applied to ensure the validity and predictive ability of the numerical models. In this process, the parameters of the analytical models were systematically adjusted by comparing them with the data obtained from the experimental modal analyses. The agreement between the analytical and experimental findings supported the overall reliability and validity of the numerical representations developed for the reinforced concrete frame structures.

2. Materials and methods

This study focuses on the experimental modal analysis of small-scale, two-story reinforced concrete structures, each featuring a story height of 20 cm and a span of 20 cm. Five distinct specimens were examined as part of this research. Three of these specimens were constructed with rectangular columns, each having a cross-sectional size of 25x25 mm (Fig. 2a). The remaining two specimens incorporated circular columns, each with a diameter of 20 mm (Fig. 2b).



(a) (b)

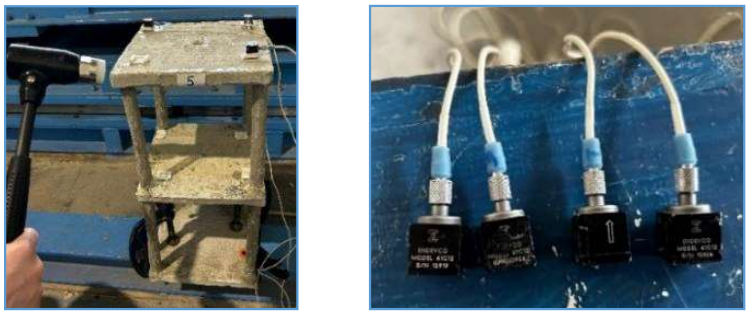
Fig. 2. Two type of specimen having a) Rectangular column cross-section b) Circular column cross-section

At the beginning of this study, finite element (FE) simulations were performed before the experimental modal analysis to find the approximate natural frequency range of the structures. This frequency range obtained from the FE models was important in determining the necessary measurement settings (e.g., sampling frequency, frequency resolution) for the experimental modal analysis.

The reinforced concrete frame structures were stimulated with a calibrated modal impact hammer. The frequency content of the impact applied by the hammer depends on the hardness of the tip used; harder tips affect a wider frequency range. As stated in the literature by Avitabile (2001), selecting the appropriate tip is important to adequately excite all structural modes relevant to modal identification. Therefore, a modal impact hammer is used with appropriate sensitivity and linearity to accurately measure the force applied to concrete structures (Fig. 3a).

We used uniaxial accelerometers to study how structures vibrate (Fig. 3b). These special sensors generate electrical signals directly proportional to the movement of a small mass inside. These signals are converted from analog to digital, allowing us to obtain precise acceleration values at the points where the sensors are placed. In this way, we can comprehensively understand the dynamic behavior of structures.

In the experimental phase of this research, transient vibrational excitations generated in structural systems by the controlled impact forces of the modal hammer were recorded using three uniaxial accelerometers. The roving hammer technique was applied. Under this methodology, accelerometers were placed at strategic points in the structural frames to record linear acceleration components along the x and y horizontal axes.



(a) (b)

Fig. 3. Test setups a) Modal hammer b) Uniaxial accelerometers

The data obtained from the experimental studies was recorded using Dewesoft signal processing software installed on a personal computer. During this process, the force signal from the modal hammer was visualized as a force-time graph in the time domain. In contrast, the vibration response signals from the accelerometers were recorded as acceleration-time graphs. To accurately analyze these time-dependent data, they were transformed into the frequency domain using the Fast Fourier Transform (FFT) algorithm integrated within the software. Subsequently, Frequency Response Functions (FRFs) that characterize the dynamic properties of the structures were calculated.

The Frequency Response Function (FRF) mathematically describes how a structure responds to an applied force. This response is usually measured by acceleration, velocity or displacement. The FRF examines the components of both the applied force and the structure's response at different frequencies. To do this, we convert time-varying signals into the frequency domain using the Fourier Transform method. This allows us to see how much the structure increases or decreases the forces at different frequencies. The FRF is a complex number representing the magnitude ratio and phase difference between the input and output at each frequency. Notably, the specific mathematical points (poles) of the FRF indicate the structure's natural vibrational frequencies. The shape of the FRF around these points indicates the damping characteristics of the structure (how fast it dampens vibrations) (Avitabile, 2001).

In the calculation of the Frequency Response Functions (FRFs) by transforming the obtained time data into the frequency domain, the following fundamental frequency response function formula was used by the software. Here, H(ω) represents the Frequency Response Function; X(ω), the Fourier Transform of the output response; F(ω), the Fourier Transform of the input force; and ω, the Frequency.

$$H(\omega) = \frac{F(\omega)}{X(\omega)} \tag{1}$$

Through this mathematical relationship, the frequency domain response of the structure to the applied force is analyzed in detail, and the structural dynamic properties (natural frequencies, damping ratios, and mode shapes) are determined.



Fig. 4. Measurement screen and detail of coherence

In the experimental studies, various impact application points were used to ensure a comprehensive determination of the structures' dynamic behavior. The structures' corner points were excited in both x and y directions, as impacting the corner points facilitates the excitation of a larger number of modes compared to impacting the center point (Mali & Singru, 2018).

The coherence function was used to evaluate the data quality. This function shows how linearly the measured output is related to the applied input. Inconsistent pulses in the measurement can lead to variations in the resonance values. Therefore, four controlled and consistent pulses were applied to each point for reliable results. If the coherence value of the pulses at a point was between 0.7 and 1, that measurement was accepted (Fig. 4). This process aims to increase the reliability of the Frequency Response Functions (FRF).



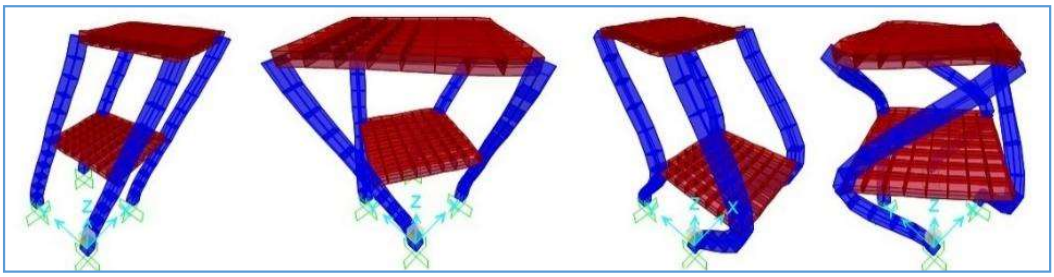
Fig. 5. Stabilization and AutoMAC diagram

The Frequency Response Functions (FRFs) generated from the acquired measurement data were converted into stabilization diagrams using the software (Fig. 5). These diagrams visually illustrate the consistency of the structural vibration frequencies and damping characteristics calculated for different mathematical model complexities (model orders). As the model complexity increases, peak points that do not show a significant change in frequency and damping values, i.e., remain "stable," are marked on this diagram.

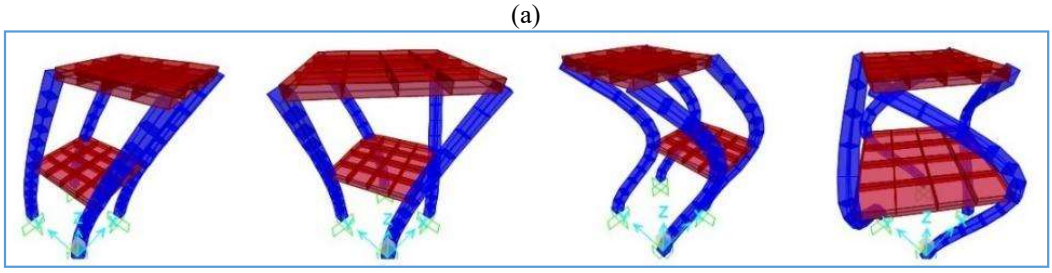
These stable peak points represent frequencies more likely to correspond to actual structural modes. Subsequently, these stable frequency values were used to generate the AutoMAC (Automated Modal Assurance Criterion) diagram. The AutoMAC diagram evaluates the similarity and consistency between the vibration patterns at different measurement points. This process helps identify "significant" physically meaningful " vibration modes, thus avoiding misleading results. These stages are crucial for enhancing the accuracy and reliability of the structural dynamic properties obtained from the experimental data (Dewesoft).

The SAP2000 models for samples given in Fig. 2a and Fig. 2b was developed using centroid lines of elements and midplanes for slabs. The models were generated separately for calibration. Calibration was made according to the modulus of elasticity of concrete of samples. The change in modulus of elasticity affects stiffness and also accounts for cracks as well. At first, the supports defined as fixed support and modulus of elasticity of concrete is taken as 24855 MPa, the default value. The effective flexural stiffness multiplier was taken as 0.7 for columns. The system is a flat slab building. The slab type definition is important for calibration, since the modal frequencies are affected by it. While “shell thin” makes column ends more like fixed ends. On the other hand, out of plane bending deformation of the slab does not accounted for the membrane, resulting decrease in the stiffness of columns. The theoretical modal analysis was done using the FE model at SAP2000 by eigenvalue analysis. In Fig. 6, the four mode shapes for different slab type definitions are given.

As can be seen from Fig. 6a and b, the nearly 90° angle of joints and “S” shape of columns can be observed from shell thin defined slab model mode shapes (Fig. 6a). On the other hand, it is more like free end for columns of membrane defined slab model mode shapes (Fig. 6b). This difference in behavior affects structural stiffness and the modal frequencies as well. Therefore, it was studied comparatively. The modal frequencies with automeshed slab models are given in Table 1.



(a)



(b)

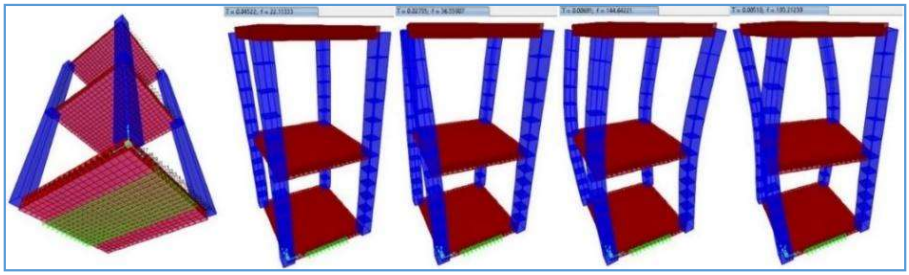
Fig. 6. SAP2000 theoretical mode shapes a) for slabs defined as shell thin b) for slabs defined as membrane

Table 1. Slab types and corresponding modal frequencies (Hz)

Slab Type	Mod 1	Mod 2	Mod 3	Mod 4
Shell Thin	62.44	86.9	203.43	268.23
Membrane	28.40	43.60	171.48	220.40

The construction of a small-scale low-strength building, like Fig. 2a and b, is a sensitive job. As a result, there are numerous governed cracks at slabs near joints. That is why membrane slab type is selected for model to describe reality. By increasing the mesh number of slab, as for shell thin model, the modal frequency is decreasing to a point. In that manner, the results given in Table 1 are obtained for 20x20 auto meshing of each slab. While gradually increasing the amount of mesh number, as for membrane, the slight change in modal frequency occurs only in torsional modes, the modal frequency for translational modes becomes constant.

Aside from slab type, the support type should defined similar to the reality. The systems have a basement, and the basement sits on a steel I beam, as can be seen from Figs. 2 a and b while the measurements of EMA are taken. The column supports are the basement itself, meaning the boundary condition of bottom of columns provided by deformation of basement. Note that not the entire basement sits on the steel beam. This situation is taken into consideration in the SAP2000 model by adding a basement, dividing it into quads, and assigning pinned supports at the nodes corresponding to the mentioned I beam and basement intersection. The bottom perspective view of the basement can be seen in Fig. 7a. The basement defined by shell thin in order to the flexural behavior of the cantilever part of basement affect the boundary condition of bottom of columns. The mode shapes for Fig. 2a building are given in Fig. 7b, c, d, and e as well.

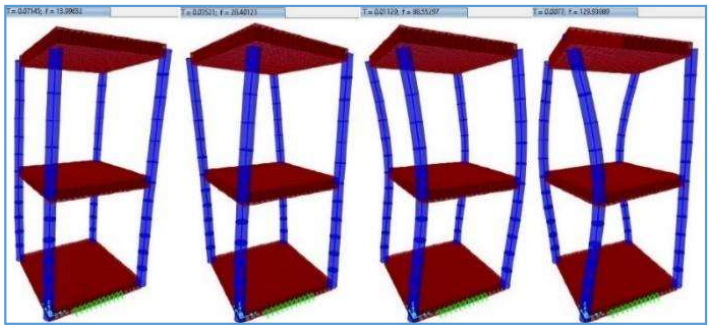


(a) (b) (c) (d) (e)

Fig. 7. SAP2000 model for rectangular column section samples a) realistic basement modeling of measured building and b) Mode 1 c) Mode 2 d) Mode 3 e) Mode 4

If one to compare Table 1 membrane defined model results with fixed support with Fig 7b, c, d, e, then the decrease in modal frequency can be observed. The basement support model provided in Fig 7a has less structural stiffness compared to fixed supported models. That is why, Fig 7 is taken as a more realistic support model and

taken into account for the results in Table 2. The same procedure (membrane slab type and realistic support modeling) was done for modeling the samples with circular cross-sectional columns (Fig. 2b) since the only difference between Fig. 2a and Fig. 2b is the columns sections. The mode shapes and corresponding modal frequencies for the samples having circular column sections are given in Fig. 8.

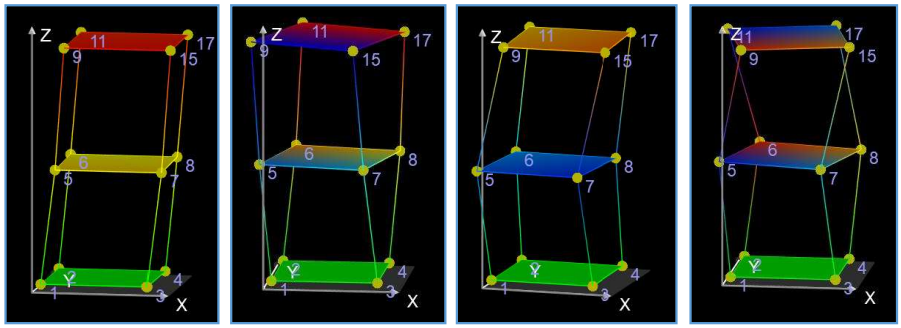


(a) (b) (c) (d)

Fig. 8. SAP2000 model for circular column section samples a) Mode 1 b) Mode 2 c) Mode 3 d) Mode 4

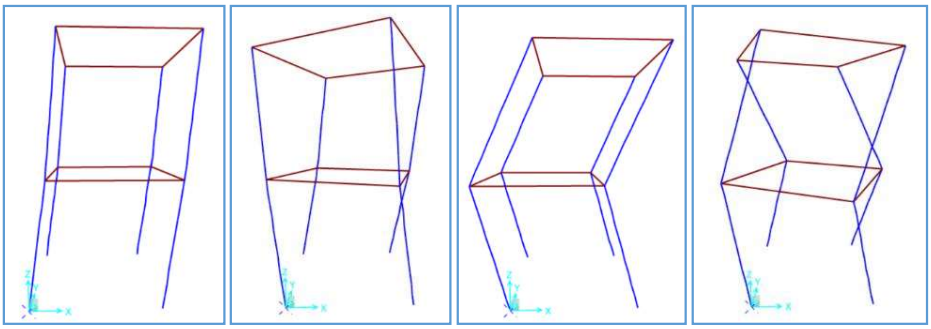
3. Results and discussion

The experimental analyses concluded by identifying four main vibration patterns (modes) for each small reinforced concrete structure we studied. This was done using special software. These fundamental modes, which show how the structures naturally vibrate, were consistently found in all samples.



(a) (b) (c) (d)

Fig. 9. Mode shapes (EMA) a) Mode 1 b) Mode 2 c) Mode 3 d) Mode 4



(a) (b) (c) (d)

Fig. 10. Mode shapes (SAP2000) a) Mode 1 b) Mode 2 c) Mode 3 d) Mode 4

The mode shapes obtained from the finite element program SAP2000 are presented in Fig. 10a, b, c and d. Observations indicate a significant overlap between the mode shapes derived from the experimental analyses and analytical results. For experiment and eigenvalue analysis, the first mode corresponds to primary translational mode (Fig. 9a and Fig. 10a), second mode corresponds to primary torsional mode (Fig. 9b and Fig. 10b), third mode corresponds to secondary translational mode (Fig. 9c and Fig. 10c) and forth mode corresponds to the secondary torsional mode (Fig. 9d and Fig. 10d). The order of these modes overlaps as EMA and FE analysis modes. This substantial agreement supports the accuracy of both the experimental methodology and the finite

element model in effectively capturing the modal characteristics of the structural behavior. These modes are important for understanding how these reinforced concrete structures might behave when forces are applied to them.

Table 2. Frequency of modes (Hz)

Sample No	Analysis	Mode 1	Mode 2	Mode 3	Mode 4	Error (%)
1	EMA[*1]	19.79	43.75	104.63	176.17	11.72
	SAP2000[*2]	22.11	36.56	144.64	193.21	
2	EMA	18.05	40.87	87.303	136.4	22.49
	SAP2000	22.11	36.56	144.64	193.21	
3	EMA	17.1	33.7	48.1	84.6	29.30
	SAP2000	22.11	36.56	144.64	193.21	
4	EMA	7.21	13.08	20.25	36.80	94.17
	SAP2000	14.00	28.40	88.55	129.94	
5	EMA	5.32	9.19	14.94	30.51	163.16
	SAP2000	14.00	28.40	88.55	129.94	

[*1]EMA: Experimental Modal Analysis
[*2]SAP2000 noncalibrated results with membrane slab definition and more realistic basement modeling

In the comparison conducted, the frequency values obtained from the experimental and finite element analyses are presented in detail in Table 2. The percent error (percentage of relative error) was calculated for the most dominant –first-mode frequencies of FE and EMA analysis. The relative error is calculated by the ratio of absolute error, which is the difference between FE and EMA analysis, to the EMA analysis result (actual value). For the results of the rectangular cross-sectional model (Fig. 2a), the finite element analysis was compared with the experimental modal analysis results. Considering the dimensions of the reinforced concrete frame, its complex behavior, and the proximity of the support assumptions made in the finite element model to the actual structural behavior, these error percentages are evaluated to be within acceptable limits for the samples having rectangular cross-sectional columns.

On the other hand, for circular cross-sectional samples as Samples No. 4 and 5 (Fig. 2b), the percentage of error obtained is quite high. This is understandable due to the poor construction of circular cross-sectional samples relative to rectangular cross-sectional samples due to the constructional hardships of small-scale buildings. The flexibility of Samples 4 and 5 could be observed during the experiment as well.

The modal damping ratios corresponding to the different mode shapes of the two-story reinforced concrete frame obtained from the experimental analyses are presented in Table 3.

Table 3. Damping ratios (%)

Sample No	Mode 1	Mode 2	Mode 3	Mode 4
1	4,833	7,54	2,56	2,01
2	12,83	10,48	6,56	6,53
3	7,09	5,06	6,15	0,62
4	2,66	4,62	4,37	2,51
5	6,22	5,12	4,13	2,87

The calibration for both Fig 2a and Fig 2b buildings was done by changing the elastic modulus of concrete. The manual calibration was done based on mode number 1, the most dominant one. The non-calibrated model (with membrane slab and more realistic basement modeling), the calibrated model, and the obtained EMA results are given in Table 4.

Table 4 shows that while the calibrated FE model and EMA modal frequency of the first mode are nearly the same, the modal frequencies of the other modes differ. The calibration was done manually and for one independent variable, i.e., the elasticity modulus of concrete. However, the factors affecting translational and torsional modes differ. Multivariable calibration might be needed to calibrate modal frequencies more than one.

Table 4. Elastic modulus of uncalibrated and calibrated SAP2000 models and corresponding modal frequencies

Sample No	State	Elastic Modulus (MPa)	Mode 1(Hz)	Mode 2(Hz)	Mode 3(Hz)	Mode 4(Hz)
	Un-Calibrated[*1]	24855	22.11	36.56	144.64	193.21
1	Calibrated[*2]	19000	19.76	32.00	126.46	168.93
	Experimental[*3]	-	19.79	43.75	104.63	176.17
	Un-Calibrated	24855	22.11	36.56	144.64	193.21
2	Calibrated	16500	18.02	29.79	117.85	157.42
	Experimental	-	18.05	40.87	87.30	136.4
	Un-Calibrated	24855	22.11	36.56	144.64	193.21
3	Calibrated	15000	17.18	28.4	112.36	150.10
	Experimental	-	17.10	33.70	48.10	84.60
	Un-Calibrated	24855	14.00	28.40	88.55	129.94
4	Calibrated	6600	7.21	14.64	45.63	66.96
	Experimental	-	7.21	13.08	20.25	36.80
	Un-Calibrated	24855	14.00	28.40	88.55	129.94
5	Calibrated	3600	5.33	10.81	33.70	49.45
	Experimental	-	5.32	9.19	14.94	30.51

[*1] Un-Calibrated: SAP2000 noncalibrated results with membrane slab definition and more realistic basement modeling
[*2] Calibrated: SAP2000 calibration by changing the modulus of elasticity according to mode 1
[*3] Experimental: Experimental modal analysis results

4. Conclusions

Within the scope of this study, the dynamic characteristics of two-story reinforced concrete structures were thoroughly investigated using experimental and analytical methods. In the experimental modal analysis conducted in a laboratory setting, the modal hammer excitation method was employed to determine the natural frequencies and mode shapes of the structures. Simultaneously, a finite element model of the same structures was created using SAP2000 software, and theoretical modal analyses were performed.

For the beamless (flat slab) frame samples, the slab type shows importance in theoretical modal analysis due to a significant change in modal frequencies. Since constructed small-scale buildings have cracks at slabs near joints and systems have defects, the joints are assumed to not be well stiff. In that regard, slabs are modeled as membranes. Even if the shell thin definition is less assuming, the membrane definition describes the real structure more suitably. This resulted in the first mode frequency decrease to %45 of it (decreased by almost half). Also, the bottom of columns is modeled not as fixed support but connected to a basement resting on a beam (with pinned supports at middle nodes). The flexural behavior of the cantilever part of the basement (outside of the steel beam) also results in a slight decrease in modal frequencies. The decrease percentage is %22. This is the pre-state of calibration changing the elastic modulus of concrete.

Manual calibration is done by changing the modulus of elasticity concrete to describe cracks in low-strength concrete. Decreasing the modulus of elasticity affects the stiffness matrix, and modal frequencies decrease as well. The first mode is considered for calibrating FE models, and Table 4 is obtained. The difference between EMA and FE modal frequencies increases with higher mode numbers. The modulus of elasticity the first three samples (rectangular cross-sectional) would be reasonable if the compressive strength of low-strength concrete is approximately 3-5 MPa.

On the other hand, the error obtained was significantly higher for Samples 4 and 5, which are circular column buildings. Due to improper construction and manufacturing difficulty, these two samples obtained way more flexible in reality than encountered in experimental results. There are some advanced calibration methods that are way more realistic. For example, in order to calibrate other modes, other calibration approaches, such as changing joint stiffness, can be evaluated. In addition, the modulus of elasticity samples can be obtained by test equipment and can be used for calibration.

The comparison of the experimental and analytical results shows that the methods used to determine the dynamic behavior of the structures and the assumptions made in the finite element model are generally consistent and reliable. In particular, the overlap in the mode shapes and the calibrated frequency values indicate that both approaches successfully capture the fundamental dynamic characteristics of the structures. Despite potential discrepancies due to the reinforced concrete frame's geometrical complexity and the material properties' idealization, the obtained agreement supports the use of the finite element model as an effective tool for the dynamic analysis of such structures. Future research can expand the knowledge in this area with different structural configurations and advanced modeling techniques.

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