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Alternative Instrumentation Schemes for the Structural Identification of the Reinforced Concrete Field Test Structure by Ambient Vibration Measurements

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Abstract

The outcomes of the ambient vibration measurements carried out to evaluate the dynamic characteristics of the reinforced concrete field test structure were presented. The test building was designed according to Turkish Seismic Code and constructed for this research study at the field laboratory in Sakarya University. The first aim is to conduct ambient vibration tests on a full-scale field test structure to measure its modal properties for the cross-validation of a finite element model of the test structure. The second aim is to optimize the instrumentation schemes from cost and quality of data point of view. Six tri-axial accelerometers were situated in different configurations on the test structure. For every configuration ambient vibrations were recorded to measure the dynamic characteristics of the test structure. For the system identification with ambient vibration signals Enhanced Frequency Domain Decomposition (EFDD) method was used. A satisfactory match between theoretical and experimental modal parameters was deduced for certain instrumentation scheme.

Keywords: *ambient vibration, optimum instrumentation scheme, enhanced frequency domain decomposition, modal characteristics*

1. Introduction

The structural finite element models used in dynamic analyses of structures are idealizations established to characterize the real structure's responses to strong earthquake motion, winds, explosions etc. These models can be verified by performing full-scale ambient and forced vibration experiments (Ivanovic *et al.,* 2000). Both of these can be used to estimate the natural vibration modes and frequencies, and the damping ratios of full-scale buildings. This information is extremely important because it characterizes the dynamic response of the building, and therefore can be used to calibrate its elastic properties for numerical modeling, to detect the modification of its behavior after the strong earthquake and to predict its behavior under future earthquakes.

There has been a large body of literature on ambient and forced vibration since the 1930's (Carder, 1936; Hudson, 1970). Looking at only some representative studies since the 1990's, the literature review are deemed to sufficiently cover and discuss in detail relative studies on the subject of ambient and forced vibration testing (Ivanovic *et al.*, 2000; Yu *et al.*, 2008; Celebi, 1993).

In order to measure the dynamic system parameters of structures, the experimental approaches can be separated into forced vibration (experimental modal analysis), ambient vibration (operational modal analysis) and free vibration measurements. Classical Experimental Modal Analysis (EMA) calculates the transfer functions from the input (excitation) and output (response) measurements to attain modal parameters, comprises natural vibration frequencies, mode shapes, modal damping ratios and participation factors. EMA has achieved significant progress in the last 30 years. A large number of structural identification algorithms, for the cases of Single-input-single-output (SISO), to multi-input-multi-output (MIMO) models in time domain (TD), Frequency Domain (FD) and Spatial Domain (SD), have been evolved (Zhang, 2005).

Operational Modal Analysis (OMA) is a modality for extracting the structural modal parameters from ambient vibration measurements. In contrast to the experimental modal analysis technique, in this method, the measurement of the excitation forces is not required. OMA, also referred as "ambient, natural-excitation or output-only modal analysis, utilizes only response measurements of the structures in operational condition subjected to ambient or natural excitation to identify modal characteristics" (Zhang, 2005; Celebi *et al*., 1993). Although, the forced-vibration test delivers directly the dynamic characteristics of the structures, it has many difficulties to perform. A vibration generator comprises the control consoles, weights, seismometers and cables. Mounting at the top of the structures operating take longer times compared to ambient vibration measurements. There is always a possibility of

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not catching the all the significant modes of the investigated structure (Celebi *et al*., 1993).

Free vibration is provided by displacing the structural system from its equilibrium or original position, and allowing it to restore its original position. In civil structures, all vibrations die out in time, as a result of damping forces. Using free vibration as a forcing technique has been successfully applied to civil structures (Hsieh *et al*., 2005).

There are two primary objectives within the research detailed in this paper. The first objective is to conduct ambient vibration tests on a full-scale field test structure to measure its modal properties for the cross-validation of a finite element model of the test structure. Another issue for any engineering system regarding vibration measurement is the determination of the optimal instrumentation scheme (Kammer, 1990; Yao *et al.* 1992; Laory *et al.*, 2012; Chang *et al.*, 2014). The best accelerometers locations and the optimum number of instruments are required to characterize modal parameters based on vibration response. Note that both instrumentation and acquirement of measurements are rather costly tasks. The second objective is to optimize the instrumentation schemes in terms of cost and quality of data. For this purpose, a variety of structural instrumentation schemes are considered on the field test structure.

The current research paper begins with a brief description of the full-scale field test structure constructed for the experiments conducted under the supervision of the authors. The finite element analysis of the test structure followed after testing instruments were introduced. The theoretical background of the method employed for the processing of the ambient vibration measurements is discussed. The experimentally determined dynamic characteristics are crosschecked the ones derived from the finite element analysis. Finally, the most relevant results are presented.

2. Description of the Full-Scale Reinforced Concrete Field Test Structure

The building investigated in this study was designed according to the Turkish Seismic Code (TEC, 2007) and constructed at the field laboratory at Sakarya University. The two-story test structure has 2.0 m by 1.5 m floor dimensions, the story height is

Fig. 1. Construction Phases of RC Field Test Structure

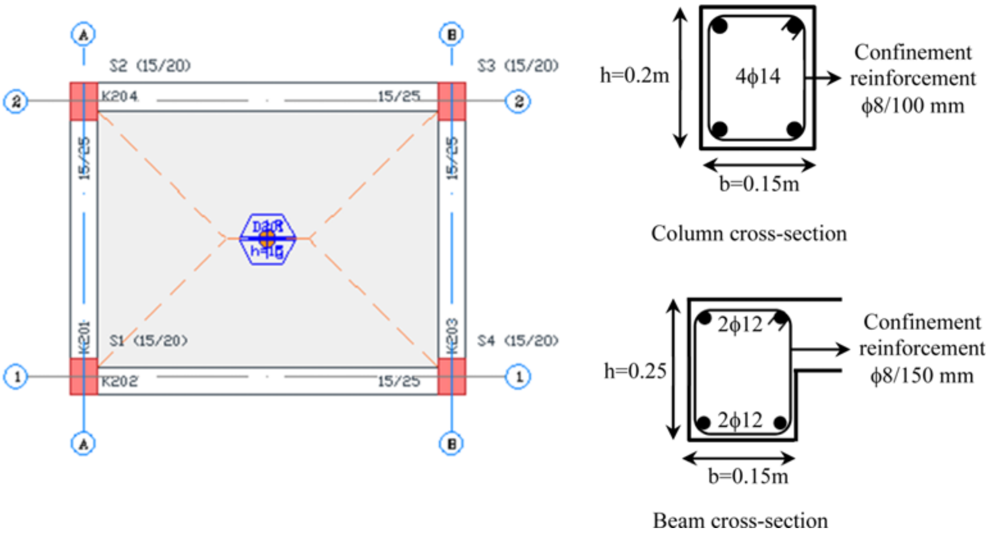


Fig. 2. Plan Layout, Column and Beam Cross Section Details

2.0 m and the slab thickness is 0.15 m (Fig. 1).

The size of the column sections is 0.15 × 0.20 m and the size of the beam sections is 0.15 × 0.25 m. Plan layout, column and beam section details are presented in Fig. 2. Ready mix grade C30 concrete was used in the construction. According to TS500 (TS500, 2000), the concrete characteristic compressive strength is specified as 30 MPa, the modulus of elasticity as $Ec = 32000$ MPa, the unit weight as 25 kN/m^3 and the limiting concrete compressive strain as $\varepsilon_u = 0.003$. The yield strength of the steel reinforcing bars is 420MPa (design strength is taken as 365 MPa), the strain at hardening is equal to 0.008, and the fracture strain is 0.10. The full-scale test structure is situated on a site with C soil deposit, as classified by NEHRP (BSCC, 2009), and has a continuous foundation with 0.5 m by 0.5 m beam dimensions. The test structure was designed stiffer in y direction as compared to the x direction.

3. Finite Element Modeling of Test Structure

Finite Element (FE) models become increasingly important for estimating the dynamic characteristics of structures in many engineering disciplines. In civil engineering FE models enable the prediction of static and dynamic properties of new design structures. Given the growing capabilities of computer technologies, FE models provide great convenience in theoretical modal analysis. For the verification of the FE modeling techniques, experimental modal analysis is generally used in structural engineering. In this study, the commercial package software Sap2000 (Computers and structures, 2011) was used for FE modeling of RC laboratory building. The geometrical and material properties of the numerical model of the building have already been described in the previous section. Columns were connected to the ground with fixed supports and all joints in the slab were assigned as rigid diaphragm. As result of the numerical modal analysis, the first six mode shapes and frequencies were identified and three mode shapes are presented (Fig. 3). The first and second modes are the translational ones in X (6.46 Hz) and Y direction (8.17 Hz) respectively, while the third mode corresponds to the torsional one (10.1Hz).

4. Testing Equipment

In order to record the ambient responses of the test structure, a variety of structural instrumentation schemes were used and the structure was instrumented with three component accelerometers as shown in Fig. 4. Mounting of the sensors are key points selected to reflect the structural characteristics best. The equipment used for the measurement and data acquisition is the DAC series accelerometers manufactured by Arel electronics (Arel, 2014). Significant Properties of DAC-3HDG series accelerometers are given in Table 1. Arel electronics has developed a wireless accelerometer network with intelligent transmission protocol. Newly designed 32 bits, simulated A2D card and other processing cards, enhanced the data quality with low noise level sensors. The data quality, acquisition capabilities of the wireless sensing system and results of the implemented analysis algorithms have been cross-validated by means of laboratory experiments in which well-known instruments Guralp and GeoSig (Beyen *et al.*,

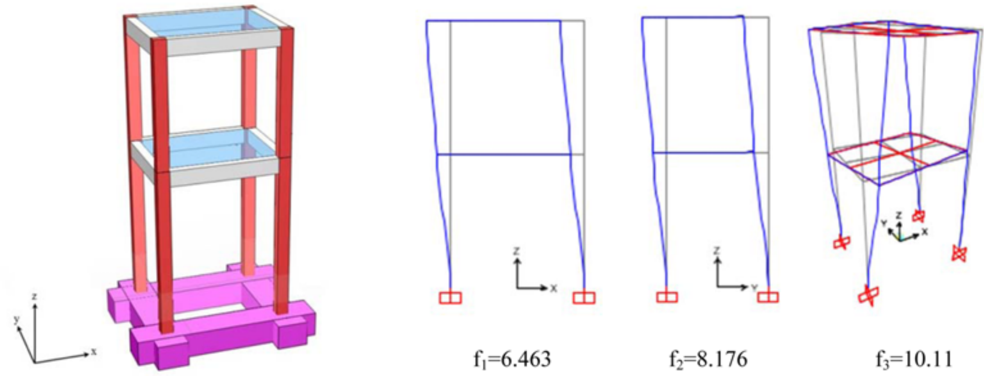


Fig. 3. Finite Element Model, Mode Shapes and Frequencies of Field Test Structure

Fig. 4. AREL DAC-3HDG Type Accelerometer and Field Support Units

Table 1. Properties of DAC-3HDG Series Accelerometers

Property	Value
Sensor Type	Colybris SF1500S.A
Technology	Axial MEMS Capacitive Accelerometers
Full Scale Range	+/- 3 g
Responsivity	2.4V/g Differential
Bandwidth	DC to 2000Hz
Self-Noise	300 ngRMS/10Hz- 300 ngRMS/100Hz- 400 ngRMS/200Hz 500 ngRMS/1000Hz
Non-Linearity	<0.1% +-1g Range
Offset Temp. Drift	100 µg/ºC

2007) were used. The current wireless monitoring system offers an economical and intelligent transmission technique for data acquisition and a very effective option for further processing in structural health monitoring and structural identification studies.

5. Frequency Domain Decomposition Theory Background

In the literature, three frequency domain output-only modal identification methods are presented. These methods are the Basic Frequency Domain Method (BFD) or peak picking method (PP); the frequency Domain Decomposition Method (FDD) and the Enhanced Frequency Domain Decomposition Method (EFDD) (Rodrigues, 2004). Recently, both FDD and EFDD methods have a widespread use due to their availability in the software ARTeMIS (Svibs, 2013). Anderson (1997) introduced some of the basic concepts of the FDD method, which was later evolved by Brincker *et al.* (2000) in a more complete way for output-only modal analysis applications. Brincker *et al*. (2001) suggested an improvement of the FDD approach, which derived from the EFDD method.

The frequency domain decomposition output-only modal identification method calculates the vibration modes using Singular Value Decomposition (SVD) of each of the spectral density matrices. This decomposition complies with a Single Degree of Freedom (SDOF) identification of the system for each singular value. In the following, the basic relationships to understand the FFD method are derived (Herlufsen *et al*., 2006). Frequency domain decomposition technique is based on the formula of input and output of a linear system that can be written in the following form (Bendat *et al.*, 1986; Brincker *et al*., 1999):

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

where $[G_{xx}(\omega)]$ is the input spectral matrix, $[G_{yy}(\omega)]$ is the output spectrum matrix, and $[H(\omega)]$ is the Frequency Response Function (FRF) matrix. The FRF matrix in the typical partial fraction form (used in classical Modal analysis), can be written in terms of poles, λ and residues, R, and assuming that the input is random in both time and space, entails a zero mean white noise distribution (i.e. $G_{xx}(\omega)$ = Const. for all the inputs) and that the damping is light. Thus, the response spectrum matrix can be written in the following final form (Rodrigues *et al*., 2004);

$$[G_{yy}(\omega)] = \sum_{k \in Sub(\omega)} \frac{d_y \psi_k \psi_k^T}{j_\omega - \lambda_k} + \frac{\overset{*}{d_k} \overset{*}{\psi_k} \overset{*}{\psi_k}^T}{j_\omega - \lambda_k^*} \tag{2}$$

where $k \in \mathrm{Sub}(\omega)$ is the set of vibration modes that contribute at the particular frequency, $\boldsymbol{\psi}_k$ is the mode shape vector and d_k is a scaling factor for the kth mode. $\lambda_k = -\sigma_k + j\,\omega_{dk}$ is the pole of the kth mode, where σ_k is the modal damping (decay constant) and ω_{dk} the damped natural frequency of the kth mode. Eq. (2) expresses the response spectral matrix in terms of the modal parameters, λ_k and $\boldsymbol{\psi}_k$ and of the scaling factor, d_k, which is governed by the excitation.

The EFDD method (Brickner *et al.*, 2001) is closely related with the FDD technique, with only some additional procedures for the evaluation of damping and enhancing the estimates of the frequencies and mode shapes of the system. In the EFDD method, the analysis of the singular values spectra takes a further step forward (Rodrigues *et al*., 2004).

6. Ambient Vibration Measurements

The field test structure was instrumented with six DAC-3HDG tri-axial accelerometers which were deployed at first and second floors. Although each DAC-3HDG accelerometer has a built-in digitizer, acquisition module and on-board flash memory with 140 hours' capacity storage, during the measurement, a centralized wireless data acquisition network system was preferred to monitor and intervene the measurement system. Time synchronization of the accelerometers was carried out by the GPS units. The duration of

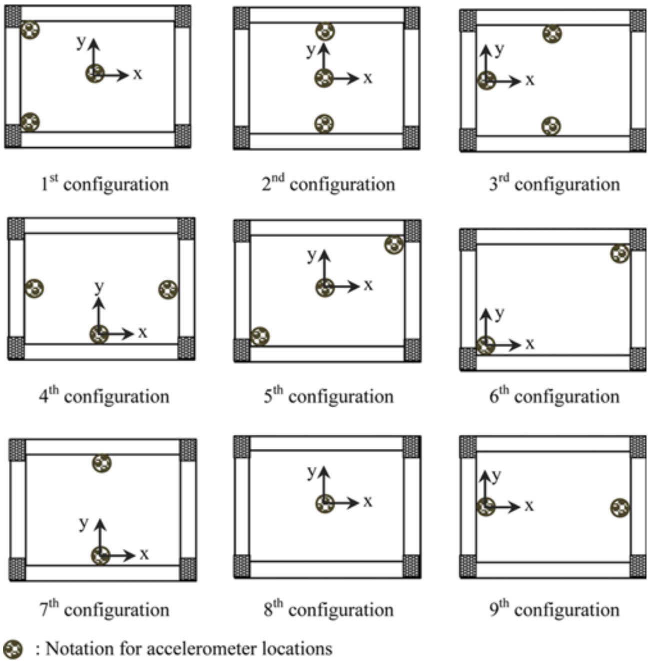


Fig. 5. Instrumentation Scheme of the Test Structure on the First and Second Floor

Fig. 6. Accelerometers Location on the Test Structure (1st configuration scheme)

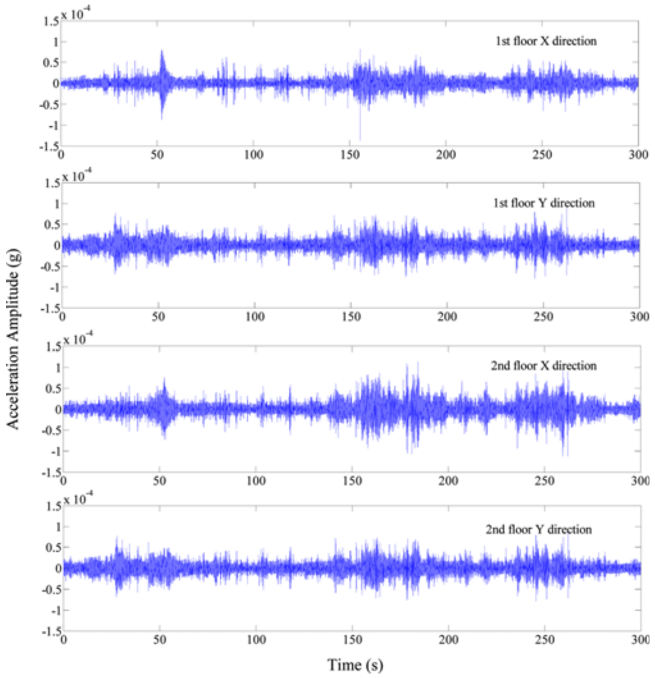


Fig. 7. Acceleration Time Series Collected During the Ambient Vibration Test of 8th Configuration

each of the recordings was 10 min, and sampling rate was set to 200 Hz at each measurement point.

The accelerometers positions were rearranged in order to optimize the instrumentation schemes regarding cost and quality of data. Configurations of the nine instruments are shown in Fig. 5 and placement of the accelerometers in the first configuration on the building is presented in Fig. 6.

For each configuration, ambient measurements were repeated and data stored both in DAC-3HDG and in a laptop computer. Ambient response measurements and data acquisition were conducted on February 23, 2014 by the research team. The temperature was in the range of 12° to 15°C. It was sunny and there was slight wind. Acceleration time series that were collected during the ambient vibration test of the 8th configuration is presented in Fig. 7.

7. Data Processing and Modal Parameter Identification

The vibration data was recorded in a time interval of 10 minutes at a sample rate of 200 Hz for each configuration. The analysis of the recorded data was carried out dividing the time period of 10 minutes of continuous monitoring in two intervals of 5 minutes each. Some basic signal preprocessing tasks, such as linear base-line correction, high-pass and low-pass filter types, were performed to eliminate very low and very high frequency parts of data sets by 0.5-50 Hz. Filtered data sets were transferred to ARTeMIS operational modal analysis software (Svibs, 2013). In ARTeMIS, modal version 3.0, for every configuration two data sets were used to identify the modal parameters of the RC test structure. Decision of which set must be used in a configuration was given according to minimal environmental impact on results. In modal parameter identification Enhanced Frequency Domain Decomposition (EFDD) method was used. Singular values of spectral density matrices (SVSDM), for every configuration data set, were obtained in ARTeMIS (Fig. 8).

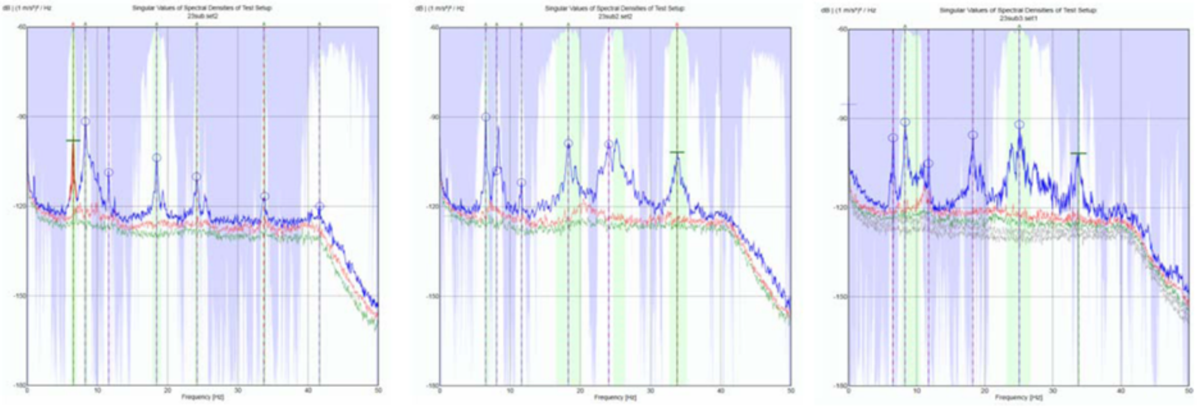
8. Results and Discussion

Using singular values of spectral density matrices (SVSDM) of each instrumentation scheme, derived from ARTeMIS software, the first six frequencies were identified experimentally. Frequency values of the building, obtained by experimental results for nine configurations, were compared with numerical analysis results (Table 2).

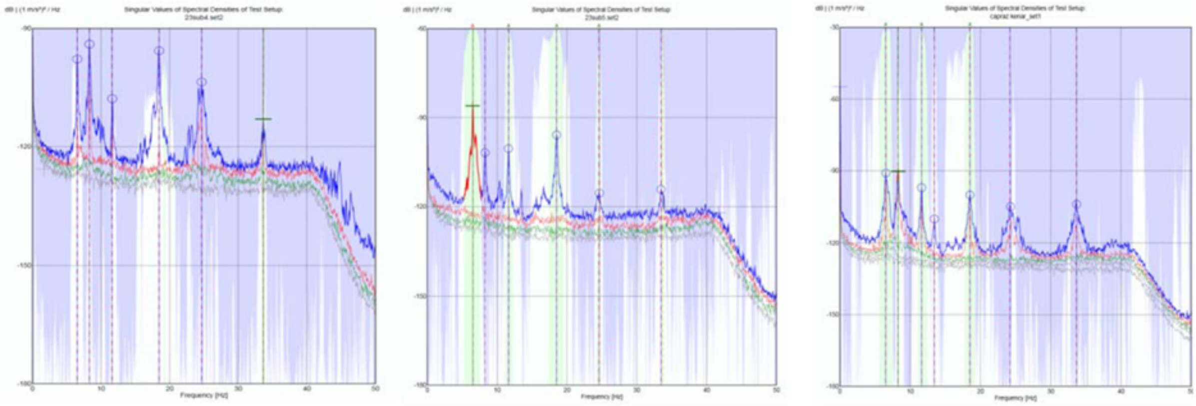
When the results are examined in Table 2, it is observed that frequency value of 13.43 Hz was identified only in configurations 5, 6 and 8. In other configurations, this frequency value could not be detected and it was considered that the frequency value of 13.43 Hz extracted due to an unidentified forced vibration source.

To assess the consistency of numerical mode shapes with experimental ones, Modal Assurance Criteria (MAC) values were used. MAC values of the mode shapes, between the nine configurations and numerical analysis, were computed with FEMtools (DDS,2014) computer program (Table 3).

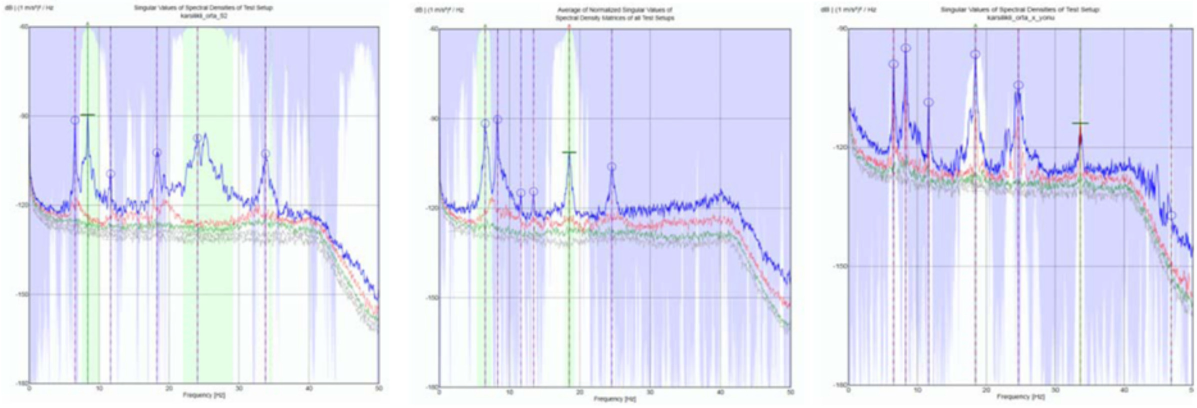
In the first four configuration results, MAC value of the third and sixth mode is very low as less than the value of 4.1%. This means that torsional modes could not be identified in these configurations. In the sixth configuration, MAC values of torsional modes are in acceptable level as higher than the value of 75%, but MAC values of translational modes are below the expected level as less than the value of 66%. In the seventh configuration the second translational mode could not be identified clearly as the MAC value is less than 1%. In the fifth



1st configuration 2nd configuration 3rd configuration



4th configuration 5th configuration 6th configuration



7th configuration 8th configuration 9th configuration

Fig. 8. SVSDM of All the Instrument Schemes

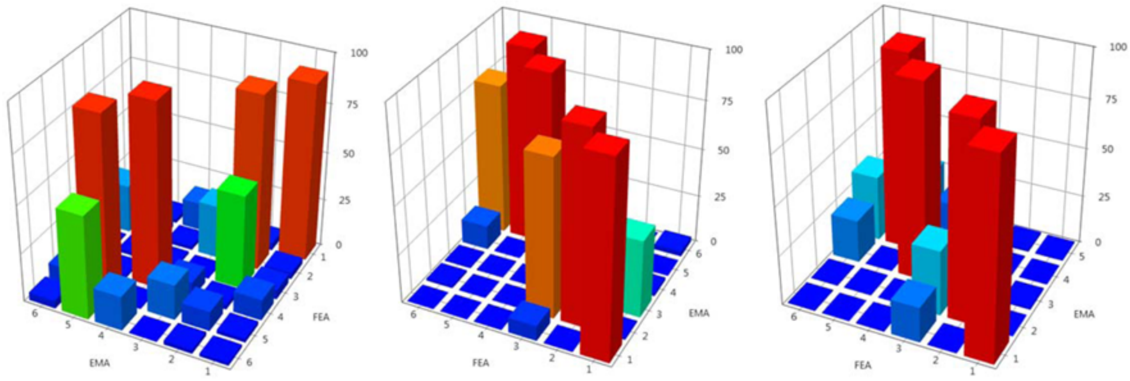
Table 2. Comparison of Numerical and Experimental Frequency Results (all frequency values are in Hertz)

Mode	FEA	Config. 1	Config. 2	Config. 3	Config. 4	Config. 5	Config. 6	Config. 7	Config. 8	Config. 9
1	6.463	6.570	6.540	6.556	6.570	6.494	6.505	6.543	6.543	6.543
2	8.176	8.296	8.105	8.277	8.296	8.252	8.269	8.349	8.300	8.300
3	10.11	11.62	11.62	11.62	11.62	11.62	11.62	11.62	11.62	11.62
4	17.27	18.45	18.31	18.29	18.45	13.43	13.42	18.26	13.43	18.40
5	22.43	24.17	24.07	24.41	24.17	18.50	18.49	24.07	18.50	24.65
6	26.95	33.70	33.79	33.65	33.70	24.56	24.21	33.79	24.56	33.64

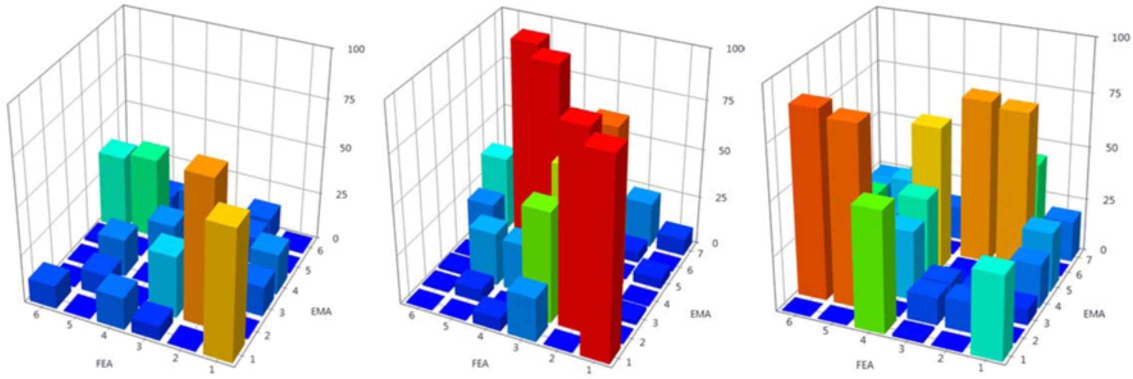
FEA: Finite element model analysis

Table 3. MAC Values of Experimental and Numerical Mode Shapes for Each Configuration (all MAC values are in percent)

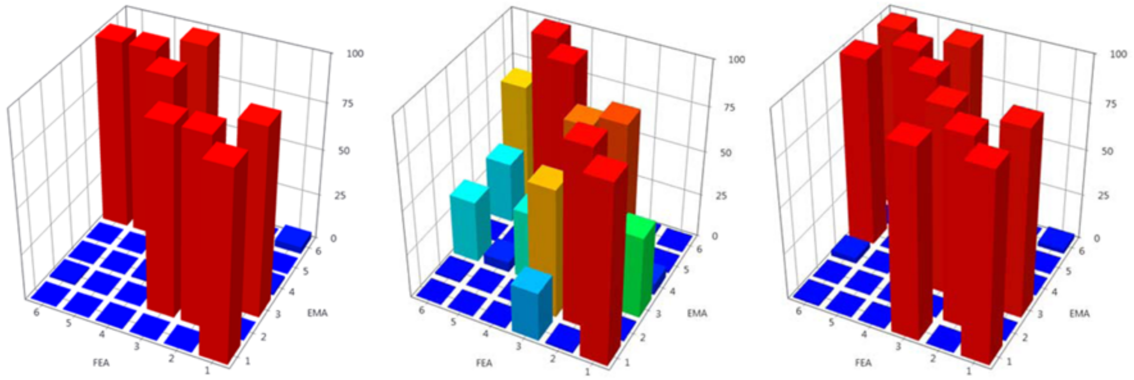
Mode	1st. MAC	2nd MAC	3rd MAC	4th MAC	5th MAC	6th MAC	7th MAC	8th MAC	9th MAC
1	91.0	99.5	99.8	68.6	99.4	38.3	99.8	99.1	99.8
2	89.9	99.0	99.7	76.9	99.4	43.2	0.70	99.2	99.9
3	2.2	1.7	-	0.1	60.8	75.3	100.0	82.7	98.6
4	95.0	99.5	99.8	21.6	99.7	66.3	99.7	99.8	99.9
5	93.3	99.7	96.5	42.4	99.4	45.1	0.10	99.4	99.7
6	4.1	0.4	0.20	0.3	1.9	86.1	100.0	35.0	97.6



1st configuration MAC 2nd configuration MAC 3rd configuration MAC



4th configuration MAC 5th configuration MAC 6th configuration MAC



7th configuration MAC 8th configuration MAC 9th configuration MAC

Note: In Fig. 9, abbreviation of FEA: finite element analysis result, EMA: experimental modal analysis result

Fig. 9. MAC Graphics of All Configurations

and eighth mode configurations for the first five mode shape MAC values are in acceptable level but at sixth MAC value for the second torsion mode is less than 35%. The best results in MAC values were obtained in the ninth configuration. All MAC values are higher than the value of 97% (Fig. 9).

9. Conclusions

In this study, modal characteristics of a reinforced concrete field test structure were identified with ambient vibration measurements and the results were cross-validated with the finite element analysis of the test structure. As a second issue, the optimal instrumentation scheme was identified to estimate modal parameters based on ambient vibration response. For this purpose, six tri-axial accelerometers were situated in nine instrumentation schemes on the test structure. For each measurement, the first six frequencies and mode shapes were taken into account for the determination of the best dynamic characteristics results. The following conclusions can be derived from this study;

1. In the first three instrumentation scheme, torsional modes were not clearly identified (the accelerometers were located in transversal direction),
2. In the fourth instrumentation scheme there were no good results identified for both translational and torsional modes,
3. In cross settlement of accelerometers (configuration 5, 6 and 8) an unexpected frequency value was determined at value of 13.43 Hz. Only in the eighth configuration (accelerometers were located at the center of gravity) MAC values, for the first three modes, were in acceptable level,
4. In seventh configuration in which accelerometers were located in transverse direction, the translational mode in Y direction could not been identified. But the identification of the translational mode in X direction and torsion mode were at acceptable level,
5. Study results proved that the ninth configuration (accelerometers were located in longitudinal direction) is the best configuration for the optimum sensor placement for the identification of the dynamic characteristics of the RC laboratory building using ambient vibration,
6. The results demonstrated that dynamic parameters' identification with ambient vibration can be very successful and it is possible to identify dynamic parameters using only two biaxial accelerometers on a floor.

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