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Sensitivity-Based Model Updating of Building Frames using Modal Test Data

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Abstract

Model updating is of significant importance in the actual analyses of real structures. The differences between experimental and numerical dynamic characteristics can be minimized by means of this procedure. This procedure can be carried out using two approaches, namely, the manual model updating and the global or local automated model updating. The local model updating is a convenient tool for all kind of structures capable of minimizing the differences mentioned previously nearly to zero and also of identifying the damage locations and monitoring structural integrity. In this way, current realistic behavior of structures can be represented by updated finite element models. This paper describes a Reinforced Concrete (RC) frame model, its ambient vibration testing, finite element modeling and sensitivity-based automated model updating. The RC frame is of ½ geometric scale with two floors and two bays in the longitudinal direction. It was built and then subjected to ambient vibration tests to determine experimentally their dynamic characteristics. Additionally, the finite element computer program ANSYS was used to determine its initial numerical dynamic characteristics. The experimental and numerical results were compared resulting in maximum differences of 38.38% between them. To minimize these differences, the finite element model was updated using the global and local automated approach using a sensitivity-based analyses with some uncertain parameters. The differences were finally reduced to 4.4% and 0.21% by the global and the local automated model updatings, respectively. It is concluded that sensitivity-based automated updating is a very effective procedure to obtain the updated finite element model which can reflect the current behavior of a structure.

Keywords: *ambient vibration test, dynamic characteristic, model updating, reinforced concrete frame*

1. Introduction

Engineering has further improved thanks to significant innovations in recent years. The calculation methods applied to simple structures in the past have begun to be applied to more complex structures. As the structures grow and become more complex, the volume of analysis has increased. In addition, the number of data needed to represent the real structure also increased. At this point, the problem has appeared that numeric model represents the real structures in actual situation.

Finite element method can give excellent results if the problem is represented correctly during modelling. But, there are many uncertainties and assumptions during constitution of the finite element models. So, the researchers have carried out nondestructive measurements and verified the experimental results with the numerical data. It has been started to minimize the differences between experimental and numerical dynamic characteristics by using some uncertain parameters such as material properties, boundary conditions, section properties etc. by finite element model updating procedure.

Finite element model updating procedure can be practiced by two different methods, namely, the manual model updating and the global or local automated model updating. Manual model updating which is made by trial and error, involves manual changes of model geometry and modelling parameters, guided by engineering judgement. Automated model updating, which is made by using special software, is performed by constitute a series of loops based on optimization procedures.

In the literature, there are many studies exist about the finite element analyses and ambient vibration measurements of different type engineering structures such as masonry structures (Gentile and Saisi, 2007; Sevim *et al*., 2011a; Altunışık *et al*., 2016; Lacanna *et al*., 2016; Russo, 2016), precast structures (Osmancıklı *et al.*, 2015), steel structures (Altunışık *et al.*, 2011; Gentile and Saisi, 2011), dams (Deinum *et al.*, 1982; Loh and Wu, 1996; Sevim *et al.*, 2011b), power plants (Nour *et al*., 2016) and buildings (Ventura *et al*., 2002; Wu and Li, 2004; Skolnik *et al*., 2007) to determine the structural response and extract the

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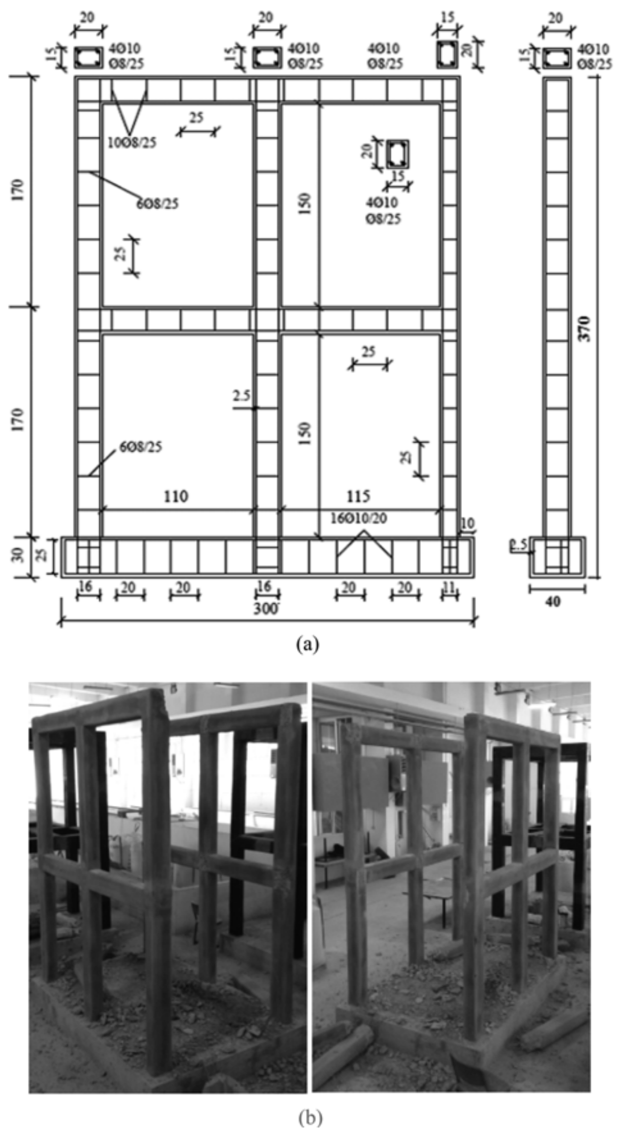
dynamic characteristics in use. However, there are not enough studies about the using of manual and sensitivity-based automated (global and local) finite element model updating procedure despite these methods has become very popular in recent years (Jensen *et al*., 2014; Lam *et al*., 2014; Sanayei and Rohela, 2014; Sanayei *et al*., 2015; Kodikara *et al*., 2016; Nasser *et al*., 2016; Sun and Büyüköztürk, 2016; Hong *et al.*, 2017; Pedram and Esfandiari, 2017; Petersen and Oiseth, 2017; Song *et al*., 2017; Wang *et al*., 2018). In order to remove this deficiency, this study considers a sensitivity-based finite element model updating of a RC building frame to minimize the differences between experimentally and numerically identified dynamic characteristics.

2. RC Building Frame Model

The Reinforced Concrete (RC) building frame model is constructed in laboratory condition to determine the initial numerical and experimental dynamic characteristics, and obtain the updated finite element model by sensitivity-based automated model updating procedure. The model has two-floor with two spans in the longitudinal direction considering ½ geometric scales without make material scaling. The frame model has two types columns with 15 × 20 cm and 20 × 15 cm dimensions and equal beams with 15 × 20 cm dimension. The dimension of openings and each floor height are selected as 140 cm and 170 cm, respectively. The raft foundation is considered to constitute the fixed base using 30 cm slab thickness. The drawings including geometrical, sectional and reinforcement details are given in Fig. 1(a). The view of RC building frame model after construction is also presented in Fig. 1(b). Low-strength concrete having 16 MPa compressive strength and S420 type reinforcement steel are considered in order to represent the general material properties for building stock in Turkey.



(a)

(b)

Fig. 1. The Drawing Details and Views of the RC frame after Construction: (a) Drawing Details (units: cm), (b) Views after Construction

2.1 Ambient Vibration Tests

Ambient vibration tests are conducted on the RC building frame model to determine its experimental dynamic characteristics such as natural frequencies, mode shapes and damping ratios. B&K 3560 data acquisition system with 17 channels, B&K 4507 and B&K 8340-type uni-axial accelerometers which have 10V/g sensitivity, uni-axial signal cables, PULSE (2006) and OMA (2006) software are used as test equipment during experimental measurement. The measurement is performed during 20 minutes. Frequency range is selected between 0 and 200 Hz. Accelerometer signals are accumulated in data acquisition system and transferred into the PULSE and OMA software's for signal processing, respectively. Dynamic characteristics are extracted using EFDD method in frequency domain and SSI method in time domain. Some views from measurement are given the Fig. 2.

Singular Values of Spectral Density Matrices (SVSDM) and the Average of Auto Spectral Densities (AASD) of the data set obtained by EFDD method of RC building frame model are given in Fig. 3. Fig. 4 shows the first three mode shapes of the model obtained by EFDD method.

The experimental dynamic characteristics are also identified using SSI method. The stabilization diagram and singular values for the first three modes are given in Fig. 5. Fig. 6 shows the first three mode shapes of the model obtained by SSI method. Experimentally identified dynamic characteristics using both methods are summarized in Table 1.

2.2 Finite Element Analyses

Finite element model of the RC building frame model is constituted in ANSYS (ANSYS, 2015) software. SOLID65 and LINK180 element types are used to represent the concrete and reinforcement steel, respectively. SOLID65 element has eight nodes, each node having three degrees of freedom of translation. This is a rigid element used for modeling concrete and reinforced concrete elements, capable of cracking, crushing and plastic deformation. LINK180 is bar element that it is a uniaxial tension

Fig. 2. Views from Experimental Measurement

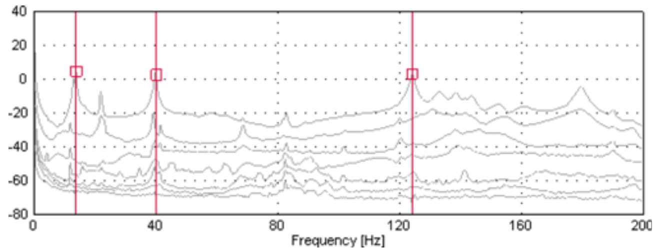


Fig. 3. SVSDM and AASD of the Data Set of RC Building Frame Model

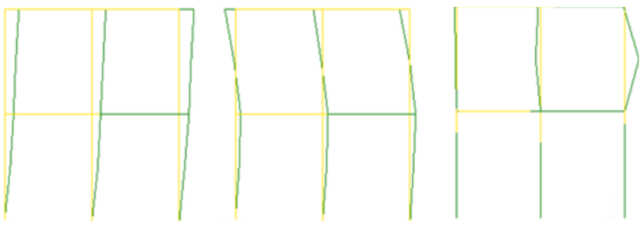


Fig. 4. The Experimental Mode Shapes Obtained by EFDD Method

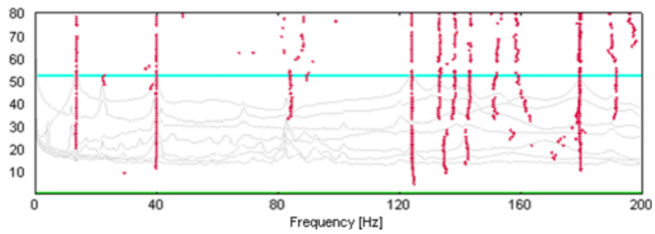


Fig. 5. The Stabilization Diagram and Singular Values

and pressure element with two nodes and has three translational degrees of freedom at each node. The reinforcements can be modeled with this element by specifying the element constants of reinforcements (material property, volume ratio and direction). Modeling of reinforcements is called as smeared reinforcement model. The reinforcements can also be modeled by drawing bar elements within the SOLID65 elements. This procedure is called as discrete reinforcement model and the reinforcement area is defined as the element constant. It is assumed that there is full

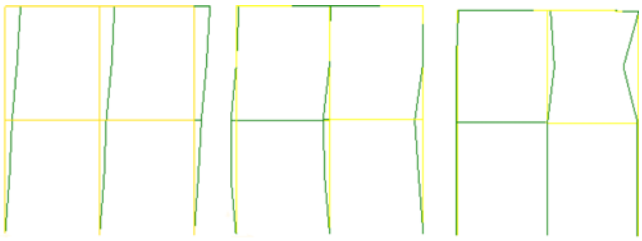


Fig. 6. The Experimental Mode Shapes Obtained by SSI Method

Table 1. Experimental Natural Frequencies of RC Building Frame Model

Mode Number	EFDD method		SSI method	
	Frequency (Hz)	Damping Ratio (%)	Frequency (Hz)	Damping Ratio (%)
1	13.898	1.022	13.69	0.859
2	39.907	0.613	39.93	0.432
3	123.84	0.451	124.7	0.680

adherence between concrete and reinforcement, in other words the strain rates of concrete and reinforcement are equal. At this point, it can be understood that concrete and reinforcement share the same nodes. RC behavior is achieved by working together with reinforcements and concrete.

Initial finite element model of RC building frame model and reinforcement layout is given in Fig. 7. Low-strength concrete having 16 MPa compressive strength and S420 type reinforcement steel are considered in order to represent the general material properties for building stock in Turkey. The material properties used in the initial finite element model are summarized in Table 2.

The modal analysis is performed to determine the numerical dynamic characteristics. First three natural frequencies are obtained as 18.012 Hz, 55.225 Hz and 149.47 Hz, respectively. The mode shapes obtained similar to the experimental mode shapes is presented in Fig. 8. To evaluate the harmony between experimental and numerical results, the maximum differences

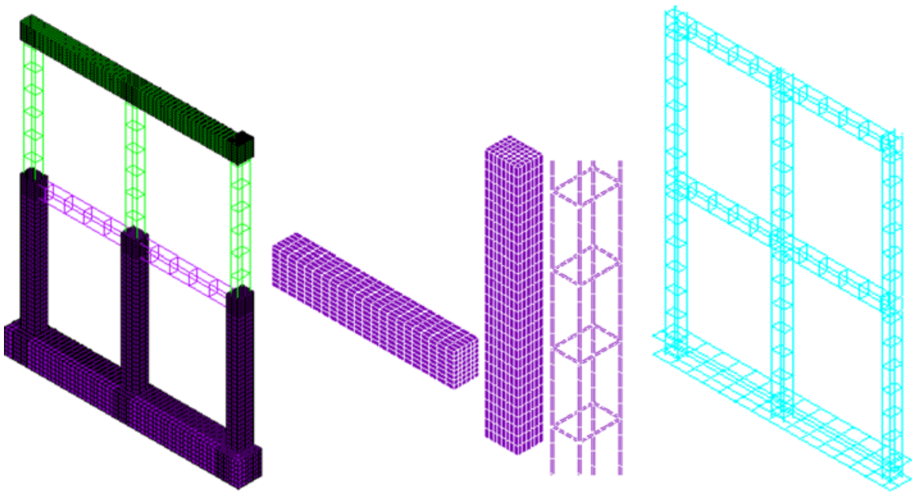


Fig. 7. Initial Finite Element Model of RC Building Frame

Table 2. Material Properties Considered in the Analyses

Material	Material Properties			
	Strength (MPa)	Young modulus (MPa)	Poisson Ratio	Density (kg/m^3)
Concrete	16	27000	0.2	2400
Rein. Steel	420	210000	0.3	7856

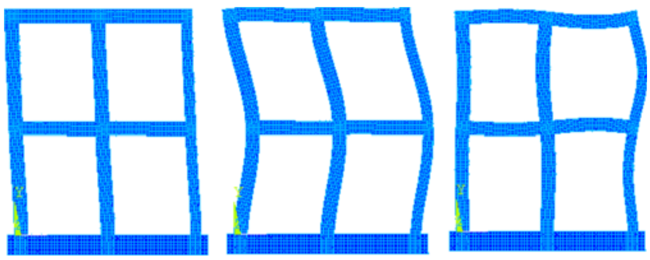


Fig. 8. The First Three Numerical Mode Shapes

Table 3. Comparison of Experimental and Numerical Frequencies with MAC values

Mode Number	Frequency (Hz)			
	Experimental	Numerical	Diff. (%)	MAC Value (%)
1	13.898	18.012	29.60	96.4
2	39.907	55.225	38.38	98.5
3	123.84	149.47	20.70	72.3

are calculated (Table 3) and Modal Assurance Criterion (MAC) is plotted (Fig. 9).

It can be seen in the Table 3 that the maximum differences is obtained very high as 38.38% for second mode. So, it can be stated that the initial finite element model cannot simulate the laboratory RC building frame model and should be updated to minimize the differences in acceptable levels. Besides, there is a good agreement between the experimentally and numerically identified mode shapes.

Figure 9 shows the MAC graphic which is generated from

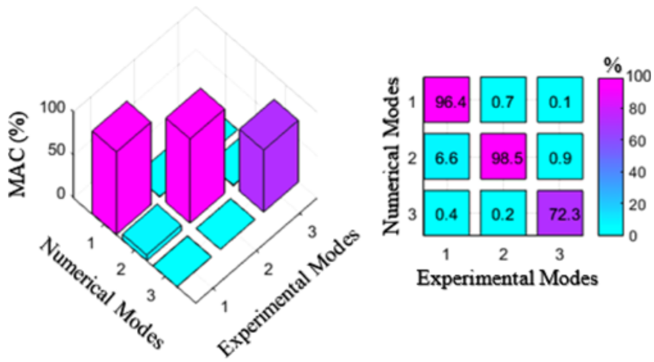


Fig. 9. MAC Values Obtained by Experimental and Numerical Results

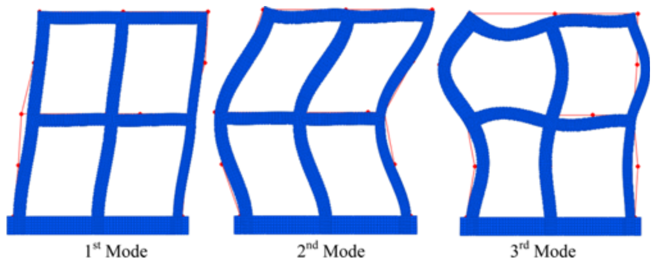


Fig. 10. Overlapping of Experimental and Numerical Mode Shapes

modal displacements (amplitudes) obtained from experimentally and numerically identified mode shapes for RC building frame model. When Fig. 9 is examined, it is seen that the MAC values between first two modes are very close to each other (the values are calculated close to 1.0). But, there is not good agreement between third modes, the MAC value is obtained as 0.723. To better understanding, experimentally and numerically identified mode shapes are overlapped in Fig. 10.

2.3 Finite Element Model Updating

The finite element model updating procedure is used to converge the initial finite element results and experimental measurements

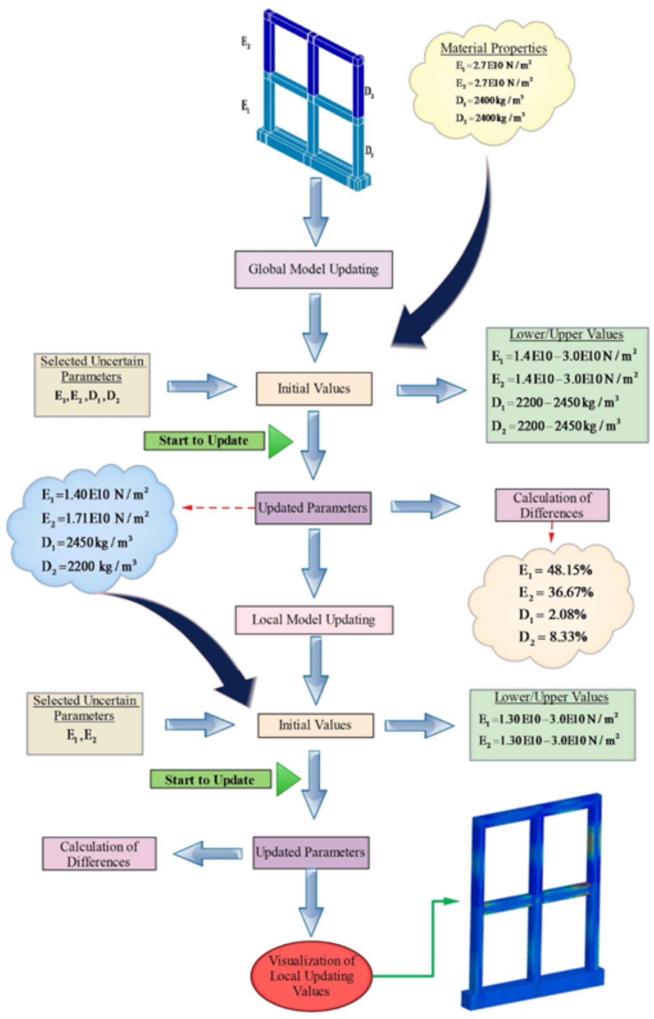


Fig. 11. Flow Chart of the Finite Element Model Updating Procedure

by using some uncertain parameters based on sensitivity analyses. Beside the alternative options, automated (global and local) model updating procedure is a preferred method to minimize the differences as soon as possible and present the local model updating effect on structural response. In the global model updating procedure, it is assumed that each structural component such as column, beam, foundation etc. has a single material property. Besides, in the local model updating procedure, it is assumed that each element after meshing can have a different material property between user defined limit values. In this paper, both methods are implemented to show the global and local model updating effect on the structural response of RC building frame model using FEMtools software (DDS, 2016).

Figure 11 presents the flow chart of the finite element model updating procedure. Firstly, global model updating procedure is considered, uncertain parameters are selected and initial parameter values are determined with lower and upper limits. It is come to conclusion that when the differences between updated numerical dynamic characteristics and the experimentally extracted values are below the 5%, the model represents the reality or current situation. Otherwise it is decided that he local model updating procedure is necessary. In this method, the material properties obtained from the global model updating procedure are selected as initial parameter values. Same to the global model updating, local model updating procedure is performed by selection of uncertain parameters and determination of lower and upper limit values. As a result of analysis, the maximum differences are reduced below 5% nearly to 1% and damage points are identified.

2.3.1 Sensitivity-Based Parameter Estimation

The Taylor series expansion limited to linear term can express the functional relationships between the dynamic characteristics and structural parameters. Eq. (1) express this relationship below.

$$\{R_e\} = \{R_a\} + [S](\{P_u\} - \{P_o\}) \text{ or } \{\Delta R\} = [S]\{\Delta P\} \tag{1}$$

where $\{R_e\}$ is vector containing the reference system responses, $\{R_a\}$ is vector containing the predicted system responses for a given state $\{P_o\}$ of the parameter values, $\{P_u\}$ is vector containing the updated parameter values and $[S]$ is sensitivity matrix.

The responses occur in pairs that this is expressed in Eq. (1). For example, experimental response is used as reference and there is corresponding numerical response in this study. Eq. (1) is usually underdetermined and can be solved using a pseudo-inverse (least squares), weighted least squares or Bayesian technique, depending on whether weighting coefficients is added or not. Since the Taylor's expansion is truncated after the first term, the neglected higher order terms necessitate several iterations, especially when $\{\Delta R\}$ contains large values.

2.3.2 Bayesian Parameter Estimation

The Bayesian parameter estimation expression includes the use of weighting coefficients on the parameters as well as on the responses. The discrepancy between the initial model predictions and the test data is resolved by minimizing a weighted error E, given by (DDS, 2016)

$$E = \{\Delta R\}^t [C_R]\{\Delta R\} + \{\Delta P\}^t [C_P]\{\Delta P\} \tag{2}$$

The following algorithm are used to minimize this error.

$$\{P_u\} = \{P_o\} + [G]\{-\Delta R\} \tag{3}$$

with the gain matrix [G] computed as:

$$[G] = ([C_P] + [S]^t[C_R][S])^{-1}[S]^t[C_R] \tag{4}$$

This equation is valid if there are more responses than parameters. In case there are more parameters than equations, which is generally the case, the following formulation is used:

$$[G] = (C_P)^{-1}[S]^t([C_R]^{-1} + [S]([C_P])^{-1}[S]^t)^{-1} \tag{5}$$

This expression has the desirable characteristic that a matrix with dimensions equal to the number of responses has to be inverted. This number is usually low compared to the number of parameters. However, this puts a constraint on the number of responses that can be practically used since the matrix that must

Table 4. Uncertain Parameters and Limit Values for Global Model Updating

Parameter Number	Structural Element	Global Model Update			
		Parameter	Lower Limit	Upper Limit	Initial Value
1	1st floor columns, beams and foundation	E	1.4E10 (N/m^2) (-48.15%)	3E10 (N/m^2) (11.1%)	2.7E10 (N/m^2)
2	2nd floor columns and beams	E	1.4E10 (N/m^2) (-48.15%)	3E10 (N/m^2) (11.1%)	2.7E10 (N/m^2)
3	1st floor columns, beams and foundation	D	2200 (kg/m^3) (-8.33%)	2450 (kg/m^3) (2.08%)	2400 (kg/m^3)
4	2nd floor columns and beams	D	2200 (kg/m^3) (-8.33%)	2450 (kg/m^3) (2.08%)	2400 (kg/m^3)

be inverted is a fully populated, non-symmetric matrix. The number of operations required to inverse such matrix are relative to the cube of the matrix dimension. The inversion of the weighting matrices is trivial as they are diagonal.

2.3.3 Global Model Updating Procedure

The initial finite element model is imported to FEMtools with ambient vibration measurement results for global model updating procedure. Element matrices are created and modal analysis is performed to validate the solution. Possible uncertain parameters are specified with lower and upper allowable limit values for sensitivity analysis. Detail information can be found in Table 4 about these properties for global model updating. A sensitivity analysis is conducted using four uncertain (4) parameters. Fig. 12 shows the global sensitivity matrix which indicates the sensitivities of four uncertain parameters versus with first three frequencies.

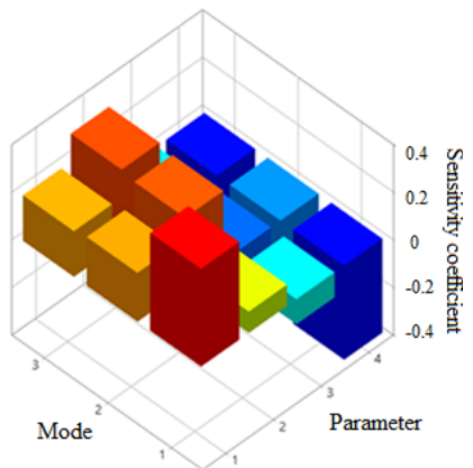


Fig. 12. Global Sensitivity Matrix of Selected Parameters

It is seen in Fig. 12 that each of selected uncertain parameters have similar effect on the frequencies. So, all parameters are taken into account during analyses. An iterative procedure is performed and stopped until acceptable difference tolerance is achieved. Table 5 lists the changes in each uncertain parameter during global model updating.

In order to present the success of this procedure, experimental measurement results are compared with global model updating results as a percentage with MAC values in Table 6. It can be easily seen that the maximum differences are reduced from 38.38% to 4.14% with global model updating. It is also observed

Table 6. Comparison of Natural Frequencies after Global Model Updating Procedure

Mode Number	Frequency (Hz)			
	EFDD	Global Model Updating	Diff. (%)	MAC Value (%)
1	13.898	13.629	-1.94	95.6
2	39.907	41.631	4.14	98.2
3	123.84	118.38	-4.4	64.7

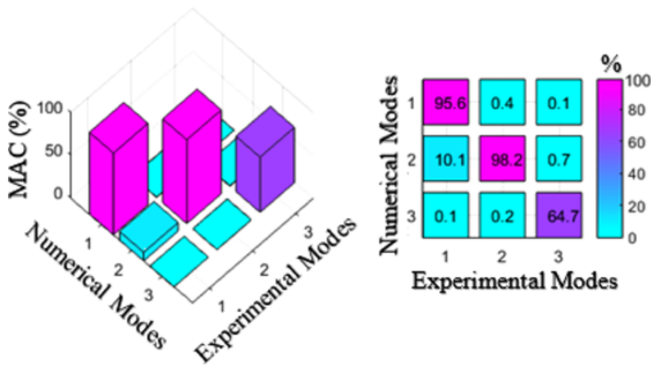


Fig. 13. MAC Graphic after Global Model Updating Procedure

Table 5. Changes in Each Uncertain Parameter During Global Model Updating

Parameter Number	Structural Element	Global Model Update			
		Parameter	Initial Value	Diff. (%)	Current Value
1	1st floor columns, beams and foundation	E	2.7E10 (N/m^2)	-48.15	1.40E10 (N/m^2)
2	2nd floor columns and beams	E	2.7E10 (N/m^2)	-36.67	1.71E10 (N/m^2)
3	1st floor columns, beams and foundation	D	2400 (kg/m^3)	2.08	2450 (kg/m^3)
4	2nd floor columns and beams	D	2400 (kg/m^3)	-8.33	2200 (kg/m^3)

that the harmony between the first and second mode shapes is also continuing. But, there is not good agreement between third modes, the MAC value is obtained as 0.647. Fig. 13 shows the MAC graphics between experimentally and numerically (global model updating) mode shapes.

2.3.4 Local Model Updating Procedure

Global model updating results are considered as a starting parameter in the local model updating procedure. The value of density is kept as constant in all elements and changes in the modulus of elasticity are taken into account. The lower and upper limits are considered as -1.3E10 (-7%) and 3E10 (114%) for 1st floor column and beams, 1.3E10 (-24%) and 3E10 (75%) for 2nd floor column and beams. The sensitivity analysis results for selected uncertain parameters are given in Fig. 14.

An iterative procedure is carried out for local model updating after sensitivity analysis. The changes in values of uncertain parameters during iterations are presented in Fig. 15. As shown in Fig. 15 that the maximum change is calculated as 120%.

Figure 16 presents the changes of material properties for each structural element on the finite element model of RC building frame.

In order to present the success of this procedure, experimental measurement results are compared with local model updating results as a percentage with MAC values in Table 7. It can be easily seen that the maximum differences are reduced from 38.38% to 4.14% with global model updating and 4.14% to 0.21% with local model updating. It is also observed that the harmony between the first and second mode shapes is also continuing. However, the MAC values for third mode decreased (from 72.3% to 64.2%) after local updating. Fig. 17 shows the MAC percentages graphically between numerical and experimental result after local model updating. Also, the comparison of numerically and experimentally natural frequencies before and after model updating (global and local updating) is summarized in Table 8.

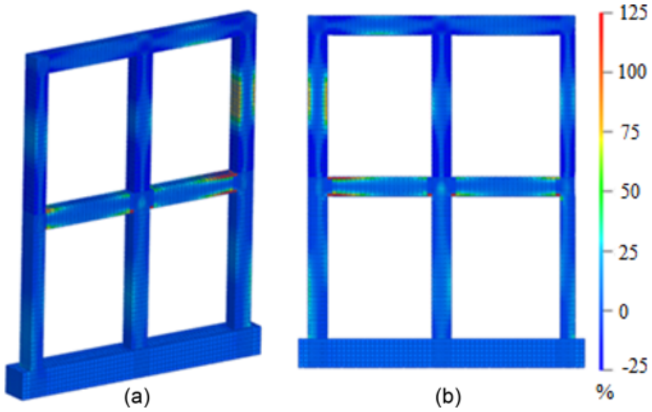


Fig. 16. Changes of Material Properties for Each Structural Element after Local Model Updating

Table 7. Comparison of Natural Frequencies after Local Model Updating Procedure

Mode Number	Frequency (Hz)			
	EFDD	Local Model Updating	Diff. (%)	MAC Value (%)
1	13.898	13.906	0.05	96.2
2	39.907	39.991	0.21	98.3
3	123.840	123.870	0.02	64.2

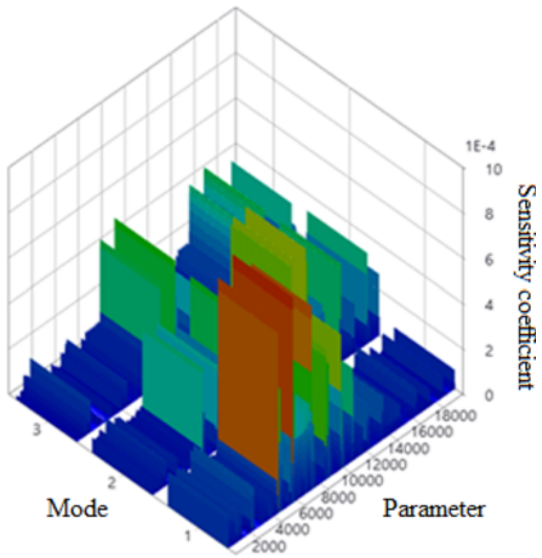


Fig. 14. Local Sensitivity Matrix of the Selected Parameters

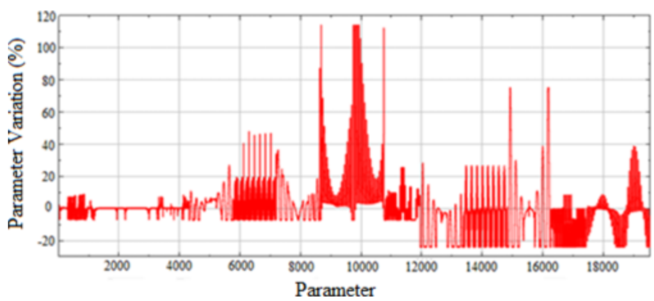


Fig. 15. Changes of Updating Parameters for Local Model Updating

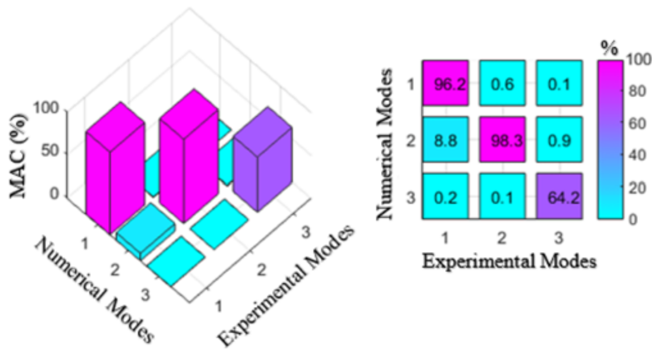


Fig. 17. MAC Graphic after Local Model Updating Procedure

Table 8. Numerical and Experimental Frequencies before / after Finite Element Model Updating

Mode Number	Frequency (Hz)						
	Experimental Frequencies (EFDD)	Numerical Frequencies					
		Initial	Global Update	Local Update	Diff. (%)	Diff. (%)	Diff. (%)
1	13.898	18.012	13.629	13.906	29.6	-1.94	0.05
2	39.907	55.225	41.631	39.991	38.38	4.14	0.21
3	123.840	149.470	118.38	123.870	20.7	-4.4	0.02

3. Conclusions

This paper describes a RC building frame model, its ambient vibration testing, finite element modelling and sensitivity-based automated model updating. A RC frame model having two-floor with two spans in the longitudinal direction considering ½ geometric scales is built in laboratory. According to the study following conclusions can be drawn.

1. From the ambient vibration test, the first three natural frequencies are obtained as 13.898 Hz, 39.907 Hz and 123.84 Hz by EFDD method and 13.69 Hz, 39.93 Hz and 124.7 Hz by SSI method, respectively. Good agreement is found between experimentally identified mode shapes, but there is no correlation in damping ratios. These high differences are typically found in practice what indicates that higher excitation levels are required to accurately capture the damping ratios.
2. From the finite element analyses, the first three natural frequencies are extracted as 18.012 Hz, 55.225 Hz and 149.47 Hz, respectively. Maximum difference is calculated as 38.38% for second mode between experimental and initial numerical results. It is seen that finite element model updating procedure should be employed to converge the experimental and numerical results and minimize the differences as soon as possible.
3. The MAC values between first two modes in the experimental and the initial numerical results are very close to each other (the values are calculated close to 1.0). But, there is not good agreement between third modes, the MAC value is obtained as 0.723.
4. To eliminate the differences between experimental and numerical dynamic characteristics, automated (global and local) finite element model updating procedure is conducted by sensitivity-based analyses using some uncertain parameters in FEMtools software.
5. In the global model updating, it is seen that each of selected uncertain parameters have similar effect on the frequencies. The maximum differences are reduced from 38.38% to 4.14%. It is also observed that the harmony between the first and second mode shapes is also continuing. But, there is not good agreement between third modes, the MAC value is obtained as 0.647. So, it is concluded that local model updating is required to further reduction of the differences.
6. In the local model updating, the maximum differences are reduced from 4.14% to 0.21%. The harmony between the first and second mode shapes is also continuing. However, the MAC values for third mode decreased (from 72.3% to 64.2%) after local updating.

Finite element analyses provide a great deal of easiness in solving engineering problems. However the input data must be selected correctly for the reliable results. Therefore model updating gains more importance. With the innovation of the model updating such as automated model updating, the differences can be minimized nearly zero. Also damage assessment can be specified and the results can be used as initial parameter for structural health monitoring.

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