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Vibration based damage detection in a scaled reinforced concrete building by FE model updating

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Abstract. The traditional destructive tests in damage detection require high cost, long consuming time, repairing of damaged members, etc. In addition to these, powerful equipments with advanced technology have motivated development of global vibration based damage detection methods. These methods base on observation of the changes in the structural dynamic properties and updating finite element models. The existence, location, severity and effect on the structural behavior of the damages can be identified by using these methods. The main idea in these methods is to minimize the differences between analytical and experimental natural frequencies. In this study, an application of damage detection using model updating method was presented on a one storey reinforced concrete (RC) building model. The model was designed to be 1/2 scale of a real building. The measurements on the model were performed by using ten uni-axial seismic accelerometers which were placed to the floor level. The presented damage identification procedure mainly consists of five steps: initial finite element modeling, testing of the undamaged model, finite element model calibration, testing of the damaged model, and damage detection with model updating. The elasticity modulus was selected as variable parameter for model calibration, while the inertia moment of section was selected for model updating. The first three modes were taken into consideration. The possible damaged members were estimated by considering the change ratio in the inertia moment. It was concluded that the finite element model calibration was required for structures to later evaluations such as damage, fatigue, etc. The presented model updating based procedure was very effective and useful for RC structures in the damage identification.

Keywords: damage detection; finite element modeling; modal testing; model calibration; model updating; reinforced concrete building

1. Introduction

Model updating reduce the differences between the finite element and experimental dynamic characteristics by changing structural parameters such as material and section properties, boundary conditions, etc (Roy *et al*. 1990, Imregun and 1991, Modak *et al*. 2000). Structural damage detection based on model updating is also very attractive in recent years because of high quality identification. If a structure is damaged, the structural behavior is changed depending on the

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location and size of the damage. The changes come up in the natural frequencies, mode shapes and modal damping ratios that are the dynamic characteristics of structures. Natural frequencies and mode shapes are key parameters for studying the structural dynamic behavior; they are often treated as constants for undamaged structures.

It was stated by Salehi *et al*. 2010 that the vibration-based damage identification methods can be classified as model based and non-model based according to the process to treat the measured data. The non-model based methods use only the measured data and these methods provide limited damage identification. The model-based methods identify damage by correlating a finite element model, which is usually based on the finite element theory, with test modal data of the damaged structure (Jaishi and Ren 2006, Perera and Ruiz 2008, Yun 2012, Li and Chen 2013). Comparisons of the updated model to the original one provide an indication of damage and further information on the damage location and its severity. Considering the main theme in the damage detection, four level damage identifications were defined by Rytter 1993:

Level 1- Identification the existence of damage

Level 2-Identification the location of damage

Level 3- Identification the severity of damage

Level 4- Evaluation of the effects of damage on the structural behavior.

Many studies were presented on the vibration-based damage detection methods that use changes in natural frequencies of a structure to detect damage. Ivanovic *et al*. 2000 presented the results of two detailed modal test of a 7-storey reinforced concrete building. The dynamics of a real structure were studied based on the changes of its natural frequency in different damaged or reinforced stages by Xue *et al*. 2008. Also, dynamic structural health monitoring systems have been developed, based primarily on the change in natural frequencies before and after the occurrence of damage. A similar study was performed on a 60 percent scale, 5-storey precast concrete test building by Zonta *et al*. 2008. This building was subjected to dynamic testing before and after the application of pseudo-dynamic loads. The damage effects were also evaluated by considering the changes in the natural vibration frequencies and mode shapes. A comprehensive study was presented by He and Zhu 2011. It was stated that the method has advantages over conventional nondestructive tests in detecting various types of damage, including loosening of bolted joints, using minimum measurement data. Also, it was mentioned there are some challenges associated with applications of the vibration-based damage detection method to engineering structures such as accurate modeling of structures. The construction of the finite element model usually includes some uncertainties. The uncertainties, including variability, exist in both simulation and test. It is important to recognize the sources and types of uncertainty. With respect to variability, it is useful to understand how small variations in input parameter propagate through the structure and manifest itself in the output. Uncertainty in simulation results manifests itself in two main classes: physical uncertainty and numerical uncertainty (Dascotte 2007). The physical uncertainties are namely the boundary and initial conditions, material properties, and geometry. Also, the main numerical uncertainties are conceptual modeling uncertainty, mathematical modeling uncertainty, discretization error uncertainties, numerical solution uncertainty, and human mistakes (Friswell and Mettershead 1995, Ewins 2000, Bayraktar *et al*. 2009).

Many studies on damage identification have been prepared by using vibration test results and global damage identifications were presented in literature. In this study, vibration based damage identification of a one-storey reinforced concrete building model with a 1/2 scale was presented by using FE model updating method. The change in the natural frequencies, mode shapes and modal damping ratios were revealed by considering the cover and core damages on the columns-ends. It can be concluded from the study that a complete damage evaluation requires both experimental investigations and model updating of finite element models.

2. Model udating

Model updating is defined as a process of quantifying the differences between finite element dynamic characteristics and corresponding experimental data, and then modifying the numerical values of the input parameters, such as elasticity modulus, mass density, boundary condition, in the model to obtain a valid model. Uncertainty is the mainly caused by lack of knowledge and may exist in all aspects of the modeling process. In practice, physical element properties (material, geometry) are selected as updating parameters to improve accuracy. They may also be used as indicators for stiffness or mass modifications that are required because of deficiencies in the model caused by inadequate meshing or level of detail. Variability, which can be considered as a specific type of uncertainty, refers to the variation of the physical input parameters that is mainly caused by manufacturing tolerances or in-service operation conditions (Dascotte 2007, Friswell and Mettershead 1995, Ewins 2000, Bayraktar *et al*. 2009, Femtools 2003a).

Model updating process consists of many steps which are defined below:

Step 1: Creating initial finite element model.

Step 2: Matching the nodes of experimental and analytical models.

Step 3: Comparing the experimental and numerical natural frequencies and mode shapes.

Step 4: Defining convergence criteria for the natural frequencies and mode shapes.

Step 5: Selecting parameters for model updating and defining the limit values.

Step 6: Sensitivity analysis for the selected parameter.

Step 7: Step by step solution until the convergence criteria is achieved.

The model updating approach is used for damage detection considering below steps:

Step 1: Creating initial finite element model.

Step 2: Calibrating the initial finite element model according to the undamaged case selecting the parameters as elasticity, mass density, etc.

Step 3: Updating finite element model according to the damaged case selecting the parameters as cross-section area, inertia moment, etc.

In this study, the numerical dynamic characteristics were calculated by using SAP2000 finite element analysis software (SAP2000 2008), the experimental dynamic characteristics were identified by PULSE and OMA softwares (PULSE 2006, OMA 2006) and model updating was performed by Femtools software (Femtools 2003b).

3. Applications

In this study, the applicability of the model updating based damage detection method was demonstrated on a one storey scaled reinforced concrete building model. The model was considered to be 1/2 scale of a typical building model. The model has two spans in longitudinal direction and one span in transverse direction. The height of the storey is 1.60 m. There are six columns and seven beams in 20 × 15 cm dimensions. Also, the slab thickness is 7.5 cm. The model was constructed on a rigid base with 50 cm thickness. Fig. 1 shows the dimensions of the building model and Fig. 2 demonstrates some views from construction. As shown in Fig. 1, the longitudinal bars were placed to the columns and beams.

The mechanical properties of the concrete, such as compressive strength and density, were identified by laboratory investigations. Three samples were taken from the concrete in the

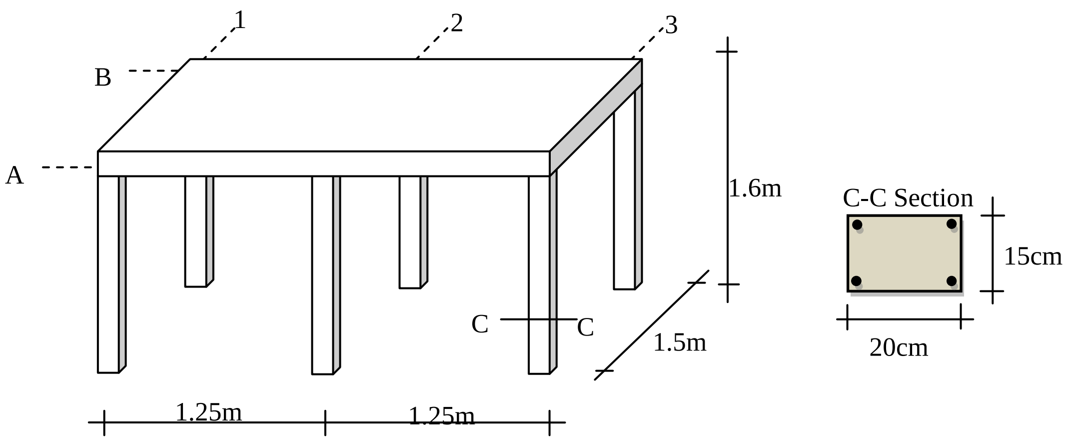


Fig. 1 The dimensions and sectional properties of the one storey building model


Fig. 2 Some views from the construction of the one storey building model

construction stage and then they were tested. The approximate mass density was identified as 2350kg/m^3. The compressive strength of the samples were measured in 16-18MPa and the elasticity modulus was considered as 22000MPa. Table 1 presents the sectional and mechanical properties of the building model.

Three different damage cases were investigated on this building model. The damages were created on the two ends of the columns. It was assumed that the cover parts of the concrete were damaged first of all. After that, the core damages were occurred. The damages were made by a rotary hammer drill. Therefore, the location and severity of the damages were assumed to be known. As mentioned previously, the damage identification procedure consists of five main steps: initial finite element (FE) modeling, testing of undamaged model, finite element model calibration, testing of damaged model, and finite element model updating for damage identification.

3.1 Initial finite element modeling

The initial finite element model was developed by using beam elements for the columns and beams, and plate elements for the slabs. The sectional properties and longitudinal bars were taken into consideration with high accuracy. The beams and plate elements were divided into many parts to reflect the real behavior of the building model. Also, the lower parts of the columns were assumed to be completely fixed in all degree of freedom. The beam-to-column connections were

Table 1 The sectional and mechanical properties of the building model

Sectional properties			Mechanical properties	
Columns	Area	3.0×10^{-2} m^2	Elasticity modulus	2.2×10^{10} N/m^2
	Inertia	1.0×10^{-4} m^4 (Longitudinal) 5.625×10^{-5} m^4 (Transverse)	Density	2350 kg/m^3
Beams	Area	3.0×10^{-2} m^2	Poisson ratio	0.20
	Inertia	1.0×10^{-4} m^4 (Bending)	Compressive strength	16-18x10^6 N/m^2
Slabs	Thickness	0.075 m		

Table 2 The first three initial natural frequencies of the building model

Mode number	Natural frequencies (Hz)
1	16.534
2	21.749
3	26.338

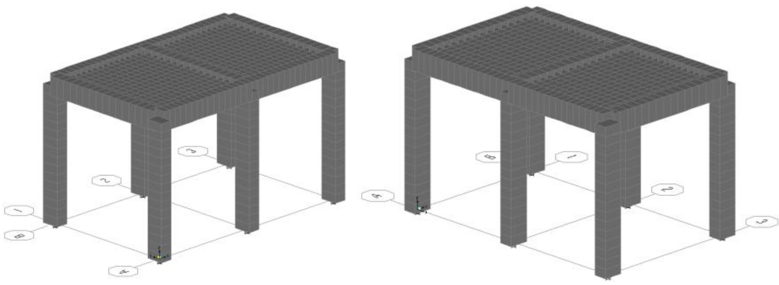
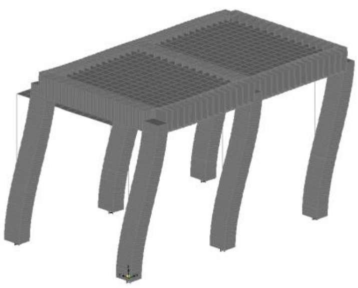
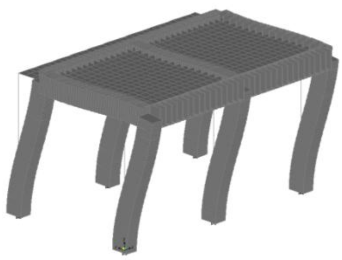


Fig. 3 The initial finite element model of the one storey reinforced concrete building model



First mode (Longitudinal)



Second mode (Transverse)

Third Mode (Torsional in slab plane)

Fig. 4 The first three modal behaviors of the building model considered as rigid. Fig. 3 demonstrates the initial finite element model of the one storey building model.

As the mechanical properties of the concrete, the values given in Table 1 were used in the initial finite element model. After the definitions, the modal analysis was employed to attain the natural frequencies and the mode shapes. Table 2 shows the initial natural frequencies of the building model. The first three natural frequencies are given in this table. They are in the 16-26Hz frequency range.

The corresponding modal behaviors of the building model are presented in Fig. 4. The first mode was a translation mode in the longitudinal direction, the second was a translation mode in the transverse direction and the third mode was a torsional mode in the slab plane.

3.2 Experimental testing for undamaged case

The undamaged dynamic characteristics were identified by modal testing. The test was performed under random loads generated by an impact hammer with rubber tip. Accelerometers were used to record structural responses under these vibrations. Uni-axial seismic accelerometers were employed in the test. They were placed to the beam-to-column connection points of the building model. Each accelerometer translates the response signal to the data acquisition system by cable. The signals were recorded in the data acquisition system according to the geometrical locations and directions during measurement duration (PULSE 2006).

In the measurement of the building model, totally ten seismic accelerometers were used as shown in Fig. 5. The measurement frequency range was selected as 0-50Hz in view of initial finite element modeling. The measurement duration was selected as five minutes.

Some views from the measurement for undamaged case are given in Fig. 6. The accelerometers, data acquisition system, connection cables and accelerometer connections are presented in these views.

The collected signals were analyzed and the modal parameters were extracted from these signals by Stochastic Subspace Identification (SSI) technique in Operational Modal Analysis software (OMA 2006). Both stabilization diagram and singular values for the first three modes were attained as given in Figs. 7-8. The stability diagrams in Fig. 7 shows the occurrence of the resonance on the each loading step. The vibration frequencies, named as singular values, and the modal damping ratios were calculated by using the stabile values.

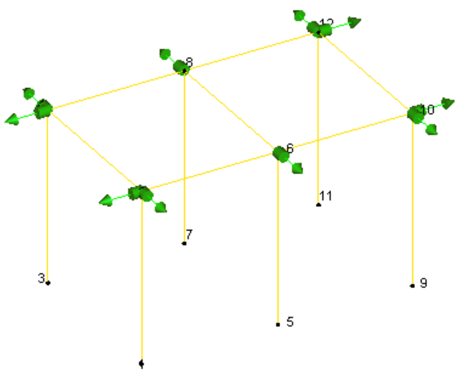


Fig. 5 The accelerometer directions and connections on the building model

Fig. 6 Some views from the undamaged case measurement

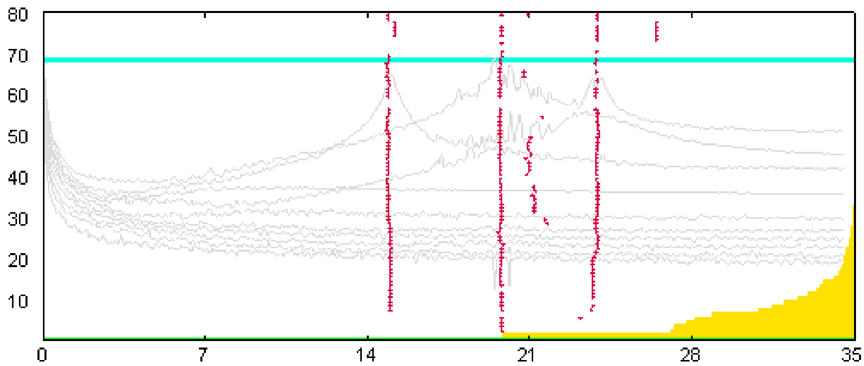


Fig. 7 The stabilization diagram for the undamaged building model

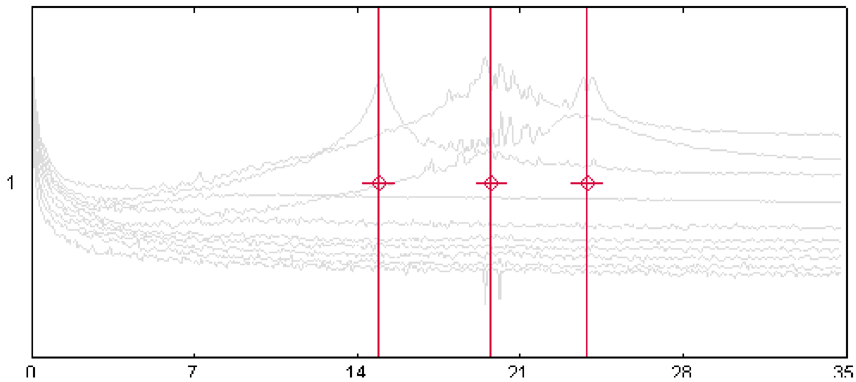
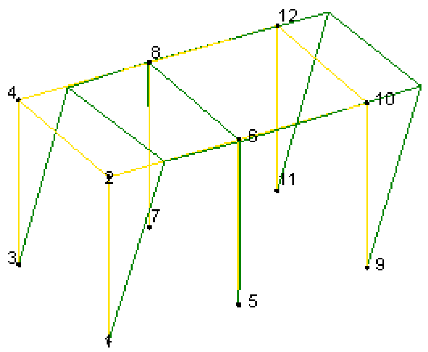


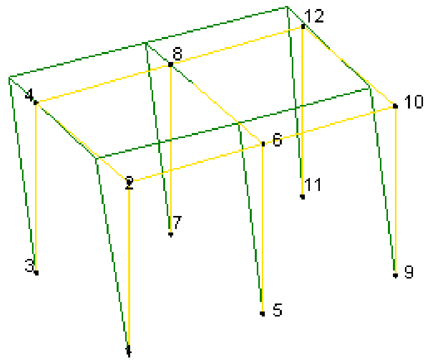
Fig. 8 The singular values diagram for the undamaged building model

Table 3 The natural frequencies and modal damping ratios for the undamaged building model

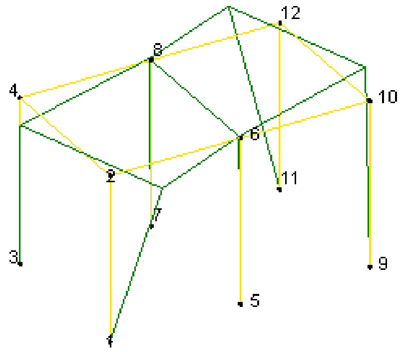
Mode Number	Natural Frequency (Hz)	Modal Damping Ratio (%)
1	14.936	1.649
2	19.751	2.471
3	23.880	0.782



First mode (Longitudinal translation)



Second mode (Transverse translation)



Third mode (Torsional in slab plane)

Fig. 9 The experimentally identified modal behaviors of the building model

The first three experimental natural frequencies and modal damping ratios are given in Table 3 for the undamaged case of the building model. Also, the experimentally identified modal behaviors of the building model are plotted in Fig. 9.

It was observed that there were some differences between the finite element and experimental natural frequencies. But, good agreements were attained in the modal behaviors. The average difference in the natural frequencies was calculated as 10.37% as shown in Table 4. Since the differences in the first three natural frequencies were close to each other, it was assumed that the differences were caused by the change in the elasticity modulus.

3.3 Calibration of the initial finite element model

In the calibration process, the uncertainties in the initial finite element model, such as elasticity modulus, boundary conditions, etc, could be considered as calibration parameters. As shown in Table 4 and stated above, the elasticity modulus was taken as variable parameter in the one storey reinforced concrete building model.

To calibrate the initial finite element model of the one storey building model, it was aimed to minimize the differences in the natural frequencies, mode shapes and modal assurance criteria by changing the elasticity modulus of the beams, columns and slabs. The maximum difference was selected as 1% of these parameters and the maximum elasticity change ratio was considered as 10%. By these definitions, iterative solutions were performed and when the aim was achieved, the

Table 4 The comparison of the finite element and experimental modal characteristics of the undamaged building model

Mode number	Natural frequency (Hz)		Difference (%)	Modal behavior	Modal assurance criteria
	Initial FE (fi)	Experimental (fe)	$\left(\frac{f_i - f_e}{f_e}\right)$		
1	14.936	16.534	10.69	Longitudinal Translation	0.993
2	19.751	21.749	10.12	Transverse Translation	0.985
3	23.880	26.338	10.29	Torsional in slab plane	0.990

Table 5 The comparison of the calibrated and experimental undamaged natural frequencies of the building model

Mode number	Natural frequencies (Hz)			Modal assurance criteria
	Undamaged	Calibrated	Difference (%)	
1	14.936	14.936	0.00	0.993
2	19.751	19.751	0.00	0.985
3	23.880	23.880	0.00	0.990

solutions were stopped. In the last step, the elasticity modulus of these members were determined as $1.7742*10^{10}$N/m^2 for columns, $2.0238*10^{10}$N/m^2 for beams and $1.8614*10^{10}$N/m^2 for slabs. The natural frequencies and modal behavior were calculated again for the calibrated elasticity values. The comparisons of the experimental and calibrated natural frequencies are given in Table 5. As shown from Table 5, the differences were completely removed by the calibration process.

3.4 Damage cases and measurements

In the one storey building model, three damage cases were taken into consideration. The damage location and severity was assumed to be known. The damage effects were created in succession. The considered damage cases were:

- ✓ Cover-concrete damages in upper parts of all columns
- ✓ Cover-concrete damages in lower parts of all columns
- ✓ Core-concrete damages in a column (A-1 column)

3.4.1 Cover-concrete damages in upper parts of all columns

Damages on building type structures due to earthquake, blast, etc occur generally on the beam-to-column joints. In many cases, the cover-concrete of the columns breaks up. Therefore, in the first damage case it was assumed that the damages come into being on the upper portion of all columns of the one storey building model. The cover-concrete were damaged by a rotary hammer drill. The thickness of the cover-concrete was 2 cm and approximately 20 cm part of the column was damaged as shown in Fig. 10.

The experimental measurement was repeated for the damaged case. In the experimental measurement, the same accelerometer configuration was used and the measurement was repeated. Some views from this damage case are given in Fig. 11. The stabilization diagram attained from this damage case is shown in Fig. 12. The first three natural frequencies and modal damping ratios were identified from this diagram as given in Table 6.

Fig. 10 The damages on the upper part of the columns

Fig. 11 Views from the damage case on the upper parts of the columns

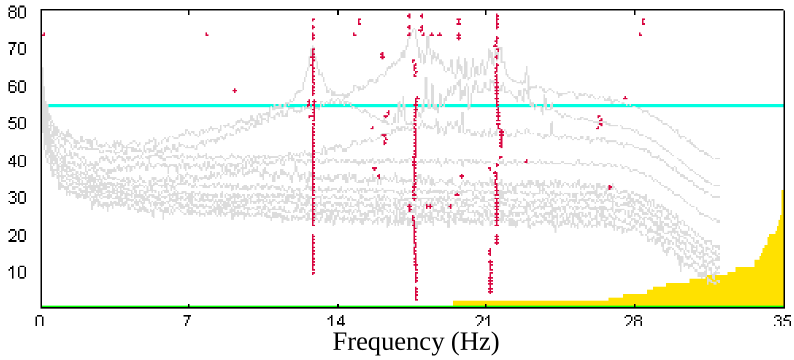


Fig. 12 The stabilization diagram for the first damage case of the building model

Table 6 The natural frequencies and modal damping ratios of the damaged case on the upper parts of the columns

Mode number	Natural frequencies (Hz)	Modal damping ratios (%)
1	12.879	0.909
2	17.685	1.550
3	21.528	1.705

3.4.2 Cover-concrete damages in lower parts of all columns

In the second damage case, it was assumed that the damages come into being on the lower portion of all columns of the one storey building model. The damages were made on the previously damaged model. The cover-concrete were damaged in a similar way. The damaged parts were approximately 20cm length. The experimental measurement was repeated on the damaged building model. The damaged model (on upper and lower parts of the columns) is given in Fig. 13.

The stabilization diagram attained from this damage case is shown in Fig. 14. The first three natural frequencies and modal damping ratios were identified from this diagram as given in Table 7.

Fig. 13 The damages on the lower parts of the column and measurement system

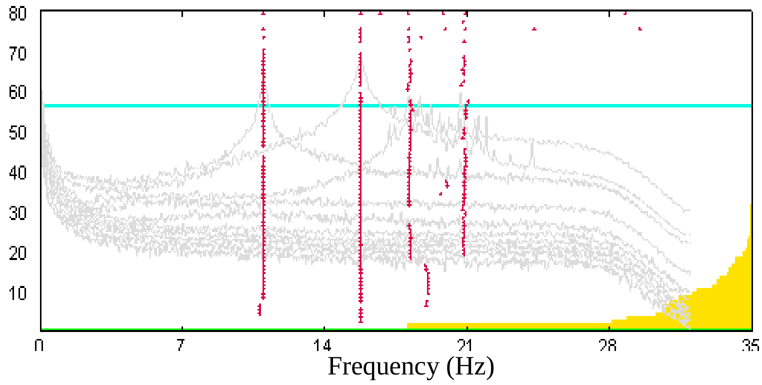


Fig. 14 The stabilization diagram for the second damage case of the building model

Table 7 The natural frequencies and modal damping ratios of the damage case on the lower parts of the columns

Mode number	Natural frequencies (Hz)	Modal damping ratios (%)
1	10.998	0.676
2	15.760	0.904
3	18.241	2.038

3.4.3 Core-concrete damages in a column (A-1 column)

In the third damage case, it was assumed that the damages come into being as core damages on a corner column. The damage was made on the previously damaged model. The core-concrete was damaged in a similar way. The damaged parts were approximately 4cm length. The experimental measurement was repeated on the damaged building model. The damaged model (on upper and lower parts of the columns and core on a column) is given in Fig. 15.

The stabilization diagram attained from this damage case is shown in Fig. 16. The first three natural frequencies and modal damping ratios were identified from this diagram as given in Table 8.

Fig. 15 The damage case for the core-concrete on the upper part of a corner column

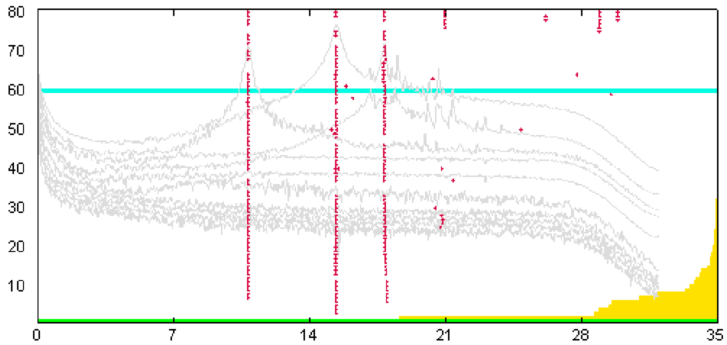


Fig. 16 The stabilization diagram for the third damage case of the building model

Table 8 The natural frequencies and modal damping ratios of the damage case on the core of a corner column

Mode number	Natural frequencies (Hz)	Modal damping ratios (%)
1	10.856	0.470
2	15.402	0.760
3	17.890	1.151

3.5 Damage Identification of the building model

3.5.1 Cover-concrete damages in upper parts of all columns

First of all, the existence of damage was determined. For this purpose, the most effective method is comparing the natural frequencies from undamaged and damaged cases. Table 9 shows the natural frequencies from the calibrated finite element model and first damage case.

From Table 9, it can be seen that there are big differences in the natural frequencies. Also, the difference was raised to 15.97% in the first mode. These were considered as the sign of damages on the building model.

After that, the locations of the damages were identified. For this purpose, the calibrated model was updated by taking the inertia moment of section as updated parameter. As the calibration process, the updating process follows the same steps. To identify the effect of inertia moment on the modal behaviors, the sensitivity analysis was performed. The results of sensitivity analysis are given for each mode shapes in Fig. 17.

By minimizing the difference in the natural frequencies, the change of the inertia moment of section were identified and plotted in Fig. 18.

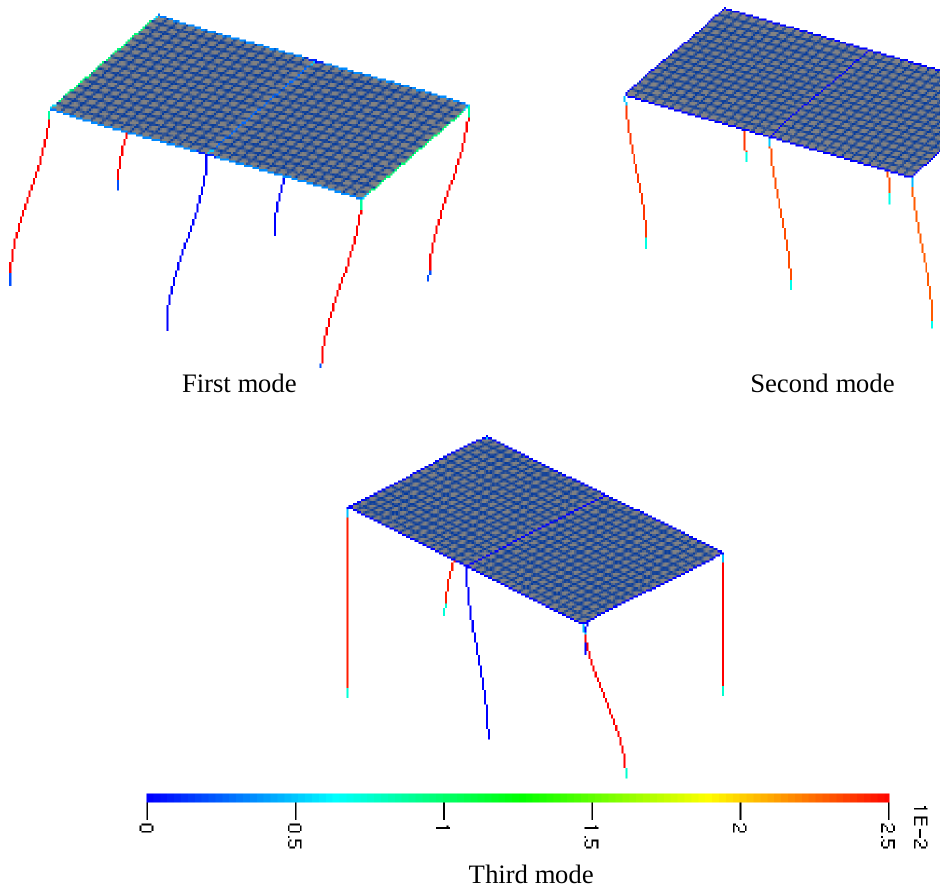


Fig. 17 The sensitivity analysis result on the first three mode shapes

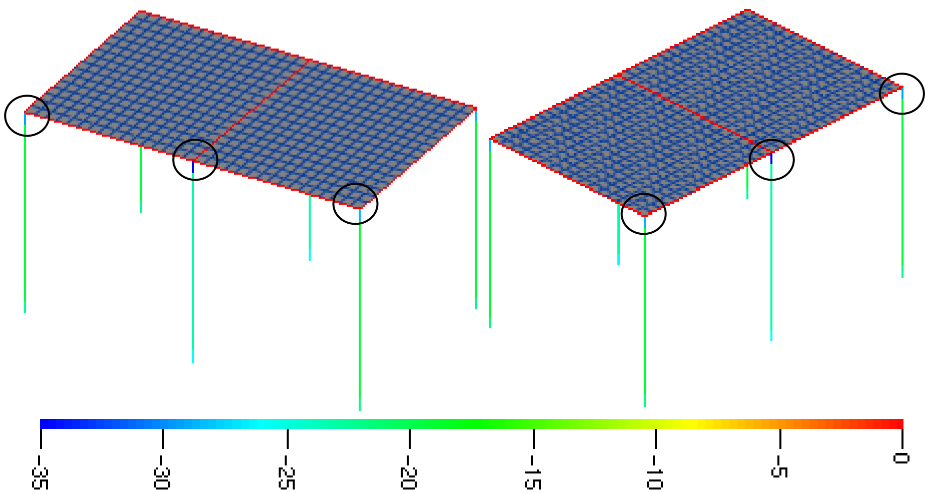


Fig. 18 The inertia moment change in the updated model for the first damage case

Table 9 The comparison of the natural frequencies from the calibrated finite element model and first damage case

Mode number	Natural frequencies (Hz)			Modal assurance criteria
	First damage case	Calibrated	Difference (%)	
1	12.879	14.936	15.97	0.993
2	17.685	19.751	11.68	0.994
3	21.528	23.880	10.93	0.986

Table 10 The updated and damaged natural frequencies for the first damage case

Mode number	Natural frequencies (Hz)			Modal assurance criteria
	Damaged	Updated	Difference (%)	
1	12.879	12.879	0.00	0.993
2	17.685	17.685	0.00	0.994
3	21.528	21.528	0.00	0.987

From Fig. 18, the maximum changes in the inertia moment were occurred in the upper parts of all columns. By comparing to real damage case, the identified damage case perfectly matched with the real damage case. For this case, the updated and damaged natural frequencies are compared in Table 10.

As seen from Table 10, a good match was attained between the natural frequencies by updating the calibrated finite element model according to the inertia moment of each section.

3.5.2 Cover-concrete damages in lower parts of all columns

The investigation for this damage case was performed on the previously developed finite element model including damages on the upper parts of the columns. The existence of damage was determined by comparing the natural frequencies from this damage case and previously updated

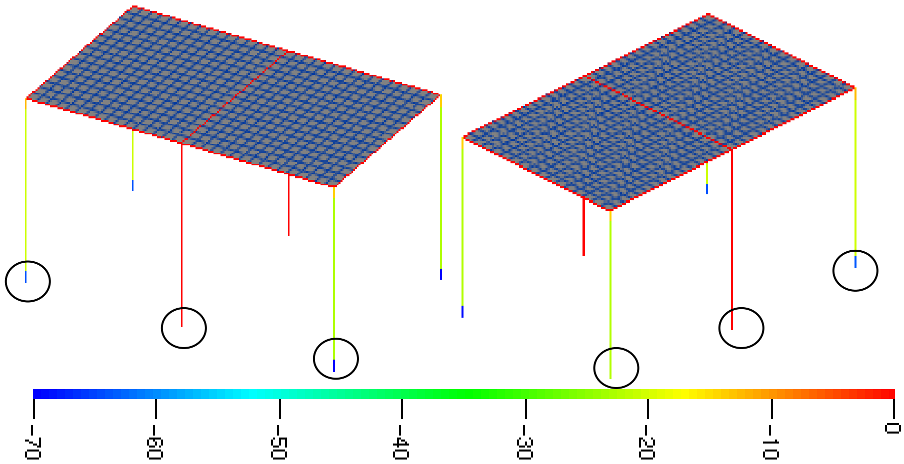


Fig. 19 The inertia moment change in the updated model for the second damage case

Table 11 The comparison of the natural frequencies from the updated finite element and second damage case

Mode number	Natural frequencies (Hz)			Modal assurance criteria
	Second damage case	Updated	Difference (%)	
1	10.998	12.879	17.10	0.995
2	15.760	17.685	12.71	0.989
3	18.241	21.528	18.44	0.989

Table 12 The updated and damaged natural frequencies for the second damage case

Mode number	Natural frequencies (Hz)			Modal assurance criteria
	Damaged	Updated	Difference (%)	
1	10.998	10.998	0.00	0.995
2	15.760	15.710	0.32	0.998
3	18.241	18.241	0.00	0.995

finite element model as given in Table 11.

It can be seen from Table 11 that big differences between the natural frequencies from this damage effects occur. The maximum difference was attained as 18.44% in the third mode. These were considered as the sign of damages on the building model. The locations of the damages were identified by updating the finite element model using the inertia moment. To identify the effect of inertia moment on the modal behaviors, the sensitivity analysis was performed. And then, by minimizing the difference in the natural, the change of the inertia moment of section were identified and plotted in Fig. 19.

From Fig. 19, the maximum changes in the inertia moment were occurred in the lower parts of all columns. It was observed that the lower parts of the corner columns were changed considerably, however the mid-columns were not changed fairly. By comparing to real damage case, the identified damage case perfectly matched with the real damage case. For this case, the updated and damaged natural frequencies are compared in Table 12. A good match was attained between the natural frequencies by updating the calibrated model according to the inertia moment of each section.

3.5.3 Core-concrete damages in a column (A-1 column)

The investigation on the last damage case was performed on the previously developed finite element model including damages on the upper and lower parts of the columns. The existence of damage was determined by comparing the natural frequencies from this damage case and previously updated finite element model as given in Table 13.

From Table 13, it can be seen that there are small differences between the natural frequencies for this damage effects. But the difference increased when the values in Table 12 were taken as reference. The maximum difference was attained as 2.30% in the third mode. These were considered as the sign of damages. The locations of the damages were identified by updating the previous finite element model. By minimizing the difference in the natural frequencies, the inertia moment changes were identified for the third damage case as shown in Fig. 20.

The maximum changes in the inertia moment were occurred in the upper part of the corner column as shown in Fig. 20. By comparing to real damage case, the identified damage case perfectly matched with the real damage case. For this case, the updated and experimental natural frequencies are compared in Table 14.

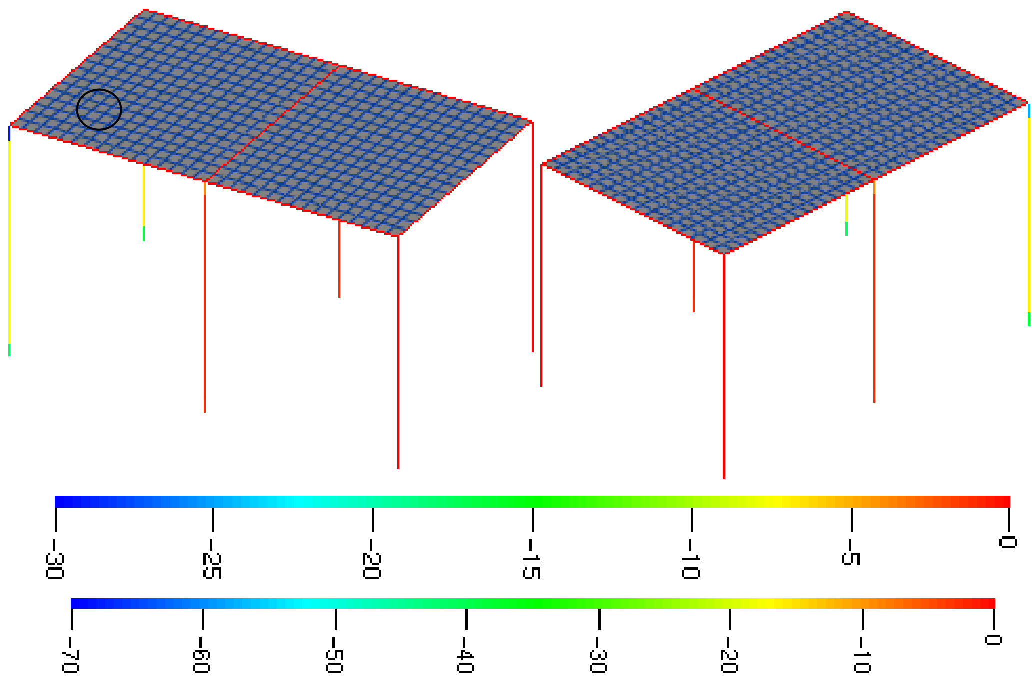


Fig. 19 The inertia moment change in the updated model for the second damage case

Table 13 The comparison of the natural frequencies from the updated finite element model and third damage case

Mode number	Natural frequencies (Hz)			Modal assurance criteria
	Third damage case	Updated	Difference (%)	
1	10.856	10.998	1.50	0.995
2	15.402	15.710	2.26	0.979
3	17.890	18.241	2.30	0.974

Table 14 The updated and damaged natural frequencies for the third damage case

Mode number	Natural frequencies (Hz)			Modal assurance criteria
	Damaged	Updated	Difference (%)	
1	10.856	10.765	0.84	0.994
2	15.402	15.394	0.06	0.998
3	17.890	17.842	0.27	0.996

4. Conclusions

An application of vibration based damage detection in RC buildings by FE model updating method was presented in this study. A one-storey reinforced concrete building model with a 1/2 scale was investigated for three damage cases. The damage detection was performed by taking into consideration the first three modes of the investigated models. It was aimed to minimize the differences between analytical and experimental natural frequencies. Some concluded remarks extracted from this study are given below:

- The natural frequencies obtained from the initial finite element model are bigger than the experimental frequencies generally. The average difference was attained as 10.37% for the first three modes. Therefore, the initial finite element models needed the calibration. The changing of the elasticity modulus in the calibration process produced good results.
- The three damage cases were considered as cover-concrete damages in upper parts of all columns, cover-concrete damages in lower parts of all columns and ore-concrete damages in a column.
- The first damage on the upper parts of all columns, the second damage on the lower parts of all columns and the core damages on a corner column decrease the natural frequencies minimally 10.93%, 12.71% and 1.50%, respectively. These showed that the dynamic characteristics of the building model varied depending on the location and extent of the damage.
- The damage existence and locations were identified by updating finite element model considering inertia moment of section as variable parameter. The identified damage locations perfectly matched with the real damage cases for all cases.
- In all cases, for model calibration and updating, the maximum difference was decreased less than 1% for the natural frequencies and good matches were attained for mode shapes.

It can be generally said that the applied method is very powerful in structural damage detection. In addition, by using this method, the updated finite element models which include damage effects are created and used for later safety evaluations such as earthquake analysis.

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