MODAL TESTING AND FINITE ELEMENT MODEL UPDATING OF TWO NOMINALLY IDENTICAL CONCRETE BUILDING FLOORS

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ABCTRACT

This paper describes a combined approach of modal testing and finite element (FE) analysis for vibration analysis of a structural system comprising two nominally identical concrete building floors located at adjacent levels. Initially, a field test of a full-scale joint two-level floor system was conducted to obtain the first five mode shapes and natural frequencies. Sensitivity-based FE model correlation and updating were then conducted to match the dynamic characteristics of the FE model with the experimental data. By setting certain indicators of good correlations between analytical and experimental models, an updated FE model comprising two nominally identical building floor was obtained

Keywords: *Modal Vibration Analysis, Model Updating, Correlation, Sensitivity Analysis, Concrete Floor.*

INTISARI

Makalah ini memaparkan gabungan pendekatan pengujian karakteristik modal dan analisa elemen hingga untuk analisa getaran suatu sistem struktur yang terdiri atas dua tingkat lantai bangunan beton yang secara nominal identik dan terletak pada level yang berturutan. Pada tahap awal, dilakukan pengujian lapangan atas suatu sistem gabungan dua tingkat lantai bangunan berskala penuh untuk mendapatkan lima pola bentuk getar dan frekuensi alamiah pertama/terendah. Kemudian, kajian korelasi dan updating atas model elemen hingga berbasiskan sensitivitas yang dilakukan dengan cara mencocokkan karakteristik dinamik hasil analisi elemen hingga dengan data eksperimen. Dengan mengatur indikator tertentu sebagai kriteria korelasi yang baik antara model analitikal dengan eksperimen diperolehlah suatu model elemen hingga dari sistem gabungan dua tingkat lantai bangunan.

Kata Kunci: Analisis Moda Getaran, Updating Model, Korelasi, Analisa Sensitivitas, Lantai Beton.

INTRODUCTION

The use of lightweight and high strength materials has enabled long-span and slender floor structures to be constructed. This type of floor may easily satisfy ultimate limit state criteria but excessive vibration may then become a serious serviceability problem.

Among others, Allen, et al. (1987), Bachmann and Ammann (1987) and Hashimoto and Abe (1994) stated that vibrations induced by humans or machines on one floor and transmitted to other floors have been regarded as a serious source of serviceability problems. Many years later, Murray (2001) commented that cases of annoying vibration have increased dramatically.

Furthermore, Widjaja (2004) have demonstrated that nominally identical floors usually develop closely spaced modes of vibration which have the potential of enhancing transmission of vibration between different floor levels.

The levels of vibration transmitted from one floor level to the others may be small. However, such levels of vibration may not be acceptable to hospital floors where an operation theatre is located, or production floors where microchips are being fabricated. By conducting analytical and experimental vibration analysis

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on full-scale floor structures, more realistic, and accurate, results can be obtained.

The research presented in this paper used the 1st and 2nd floors of a 7 storey cast in-situ reinforced concrete building (Figures 1 and 2). This was a full-scale experimental building constructed inside the Building Research Establishment (BRE) Laboratory site in Cardington, United Kingdom. Each floor level had been constructed with different types of concrete quality, reinforcement detailing and methods of construction.

Figure 1. A multi-panel concrete building used in the research work (after ICE, 2000)

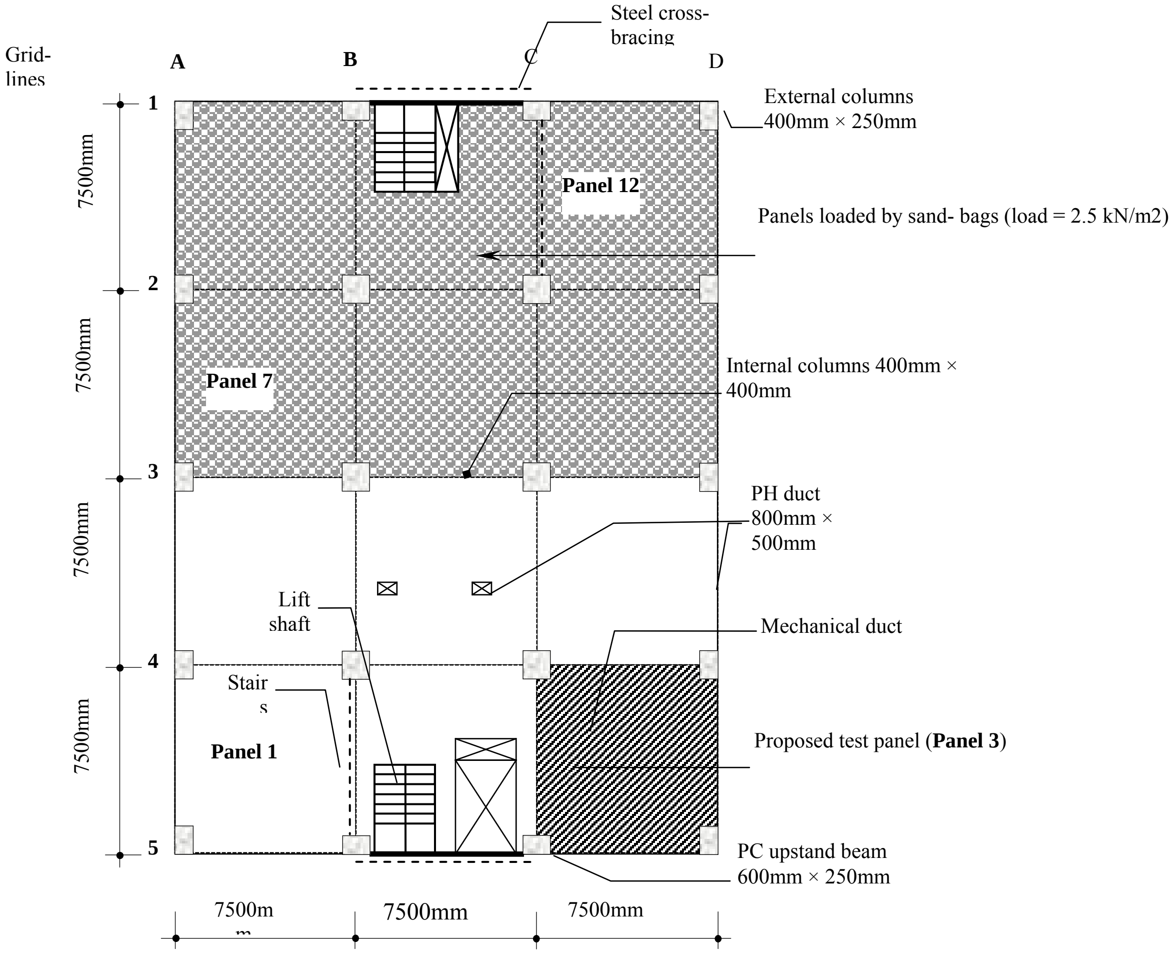

Figure 2. Typical plan view of the floor structures

Each floor had a beamless 22.5 m×30m solid flat slab with constant thickness of 250mm and was supported by columns divided into 3 by 4 bays in plan. This division resulted in 12 square panels spanning 7.5m between the columns. For the purpose of easy identification when a particular panel being mentioned in this paper, the panels are numbered from 1 to 12 for the panels on the 1st floor and 13 to 24 for the panels on the 2nd floor. The numbering for the panels on the 1st floor can be seen in Figure 2, while for the 2nd floor follows the sequence as for the panels on the 1st floor.

Prior to conducting the vibration testing, a FE model comprising two floor levels, called as a 'joint two-floor FE model', was developed for the whole floor area. This was done in order to obtain a more detailed description about dynamic behavior of the floors, and especially of the vertical bending movement of the test panel during vibration.

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The flat slabs were discretised using 4-noded thin shell elements, and all columns and upstand beams were explicitly modeled using 2-noded beam elements. The 2-floor FE model comprised of 6 by 6 shell elements per panel. The length of supporting columns for each floor level was taken as 3.75 m, which was the actual height between the floor above and below. The bottom ends of ground floor columns, which were attached to the foundation, were constrained at all six DOFs. The uppermost ends of third floor columns were also assumed to be fully restrained at all six DOFs.

FE dynamic analysis was conducted to obtain the modal properties (natural frequencies and mode shapes) of the joint two-floor FE model using FEMtools 2.0 (DDS, 2000). The pre-test FE model and the first 13 mode shapes shown in Figure 3.

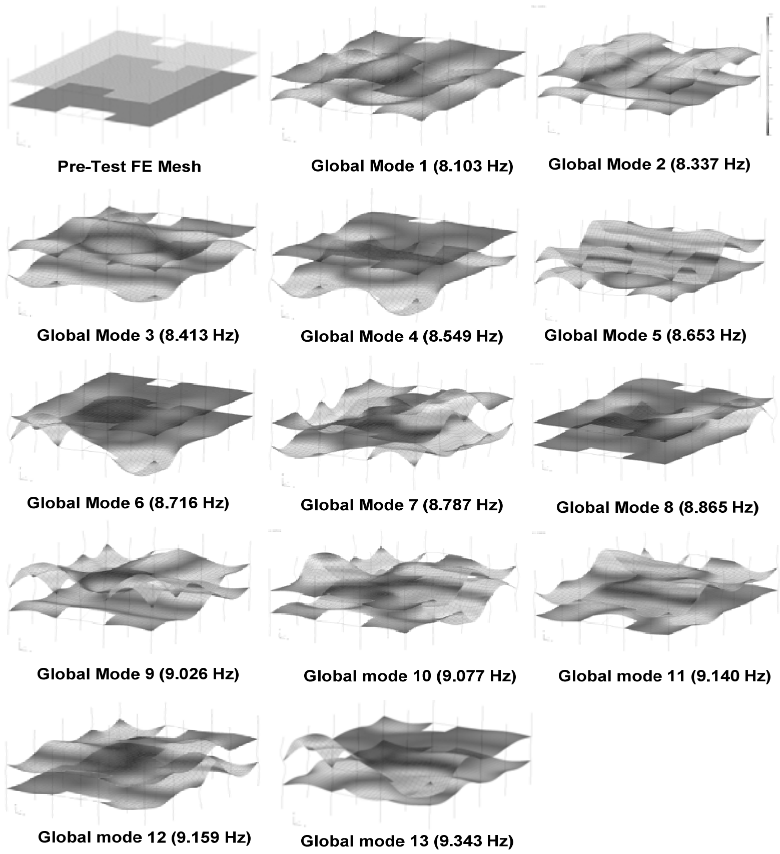


Figure 3. Pre-test FE model and the first 13 mode shapes and natural frequencies

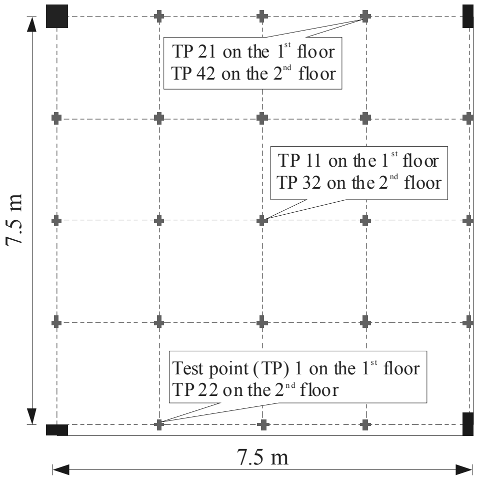


Figure 4. Proposed test grid which consists of Panels 3 (on the 1st floor level) and Panel 15 (on the 2nd floor level)

Based on this analysis a test grid was constructed as shown in Figure 4. The grid had 42 test points (TP), where TP 1 to 21 are located at Panel 3 on the 1st floor level and TP 22 to 42 are located at Panel 15 on the 2nd floor level.

A pair of corner panels of the 1st and 2nd floor levels of a full-scale experimental concrete building constructed and tested in laboratory conditions (Figures 1 and 2). The reason for conducting only the corner panels rather than the whole floors was because most of the floor areas were being loaded by sandbags for other research purposes at the time of testing. One round of testing, involving synchronous modal testing of and running and jumping measurements on the pair of cornel panels, was conducted.

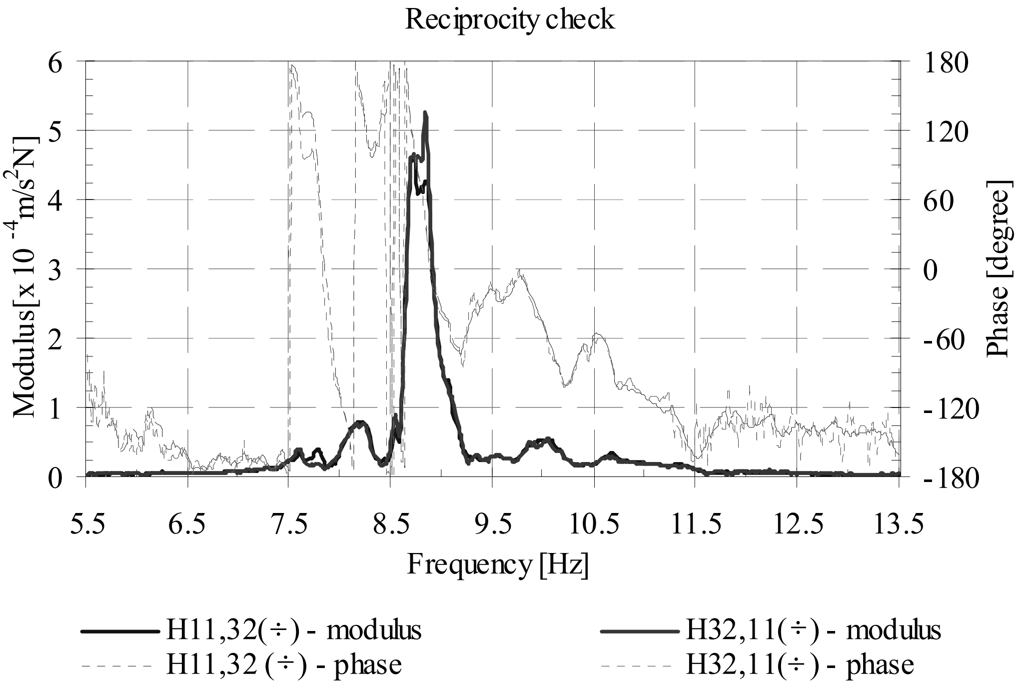


Figure 5. Reciprocity check between TP11 (on the 1st floor) and TP32 (on the 2nd floor)

After setting up the data acquisition system, the test points were marked on the test panels. Prior to conducting modal testing, a limited number of checks were performed. Firstly, the immediate repeatability check was performed by comparing the shapes of the two FRFs. It was found that the two FRFs overlaid well and the effects of background noise were small. Next, the reciprocity check was conducted on the centre points of the two corner panels to ensure that the structure obeys sufficiently well the Maxwell-Betty theorem of a linear system. It was also found the reciprocity check between the two points located at different floor levels was satisfactorily overlaid.

The key data acquisition parameters utilized in the FRF measurements of both panels are shown in Table 1. A swipe of modal testing was performed by using a roving APS Dynamics 113 electrodynamics shaker as the source of excitation. A data Physics MOBILYZER SignalCalc 430 (Data Physics Corp., 2000), which was operated using a notebook PC, was used to generate the excitation voltage signal.

As the structure had closely-spaced natural frequencies, Multi- Degree of Freedom (MDOF) curve fitting of FRFs available in MODENT (ICATS, 2000) was used. The modal properties of both panels are given in Table 2.

The experimentally estimated mode shapes of both corner panels are shown in Figure 6. It can be seen that the natural frequencies of global modes 2 and 3 at 8.625 Hz and 8.798 Hz are closely spaced. As assessed by Widjaja (2004), with the highest modal damping ratio of 2.27% is taken from mode 3, these modes satisfy the criterion for closeness of natural frequencies.

The joint two-floor FE model used for pre-test FE analysis was served as the initial FE model. The correlations between analytically calculated and experimentally estimated modal properties were done using four correlation methods:

1. Comparison of natural frequencies
2. Mode shape pairing by means of visual inspection
3. Mode shape correlation using MAC
4. Error localization using COMAC

The comparison between paired analytically calculated (FEA) and experimentally estimated (EMA) natural frequencies are presented in Table 3. The pairing was done automatically by FEMtools by initially calculating the MAC values.

Table 1. Main data acquisition parameters adopted for modal testing

Parameter description	Parameter setting/value
Data acquisition time	50 s
Frequency resolution	0.02 Hz
Frequency range of interest	Zoom 5 – 19.5 Hz
Number of Frequency domain averages	7
Force window duration (% of acquisition)	25%
Exp. window time constant	0.35
Excitation type	Logarithmic burst swept sine (chirp)
Excitation duration	10 s

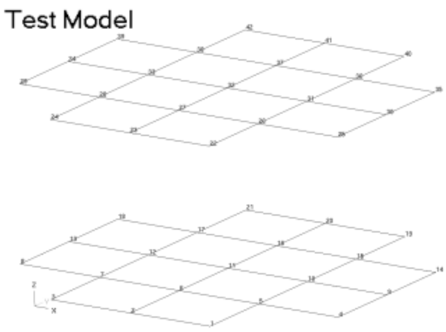
Table 2. Natural frequencies and modal damping ratios of the test panels.

Global Mode No.	Natural Freq [Hz]	Modal damping ratio [%]	Floor level of observed maximum panel mode shape amplitude
1	8.223	3.81	2^{nd}
2	8.625	2.06	1^{st}
3	8.798	2.27	2^{nd}
4	10.028	1.96	2^{nd}
5	11.345	2.05	1^{st}

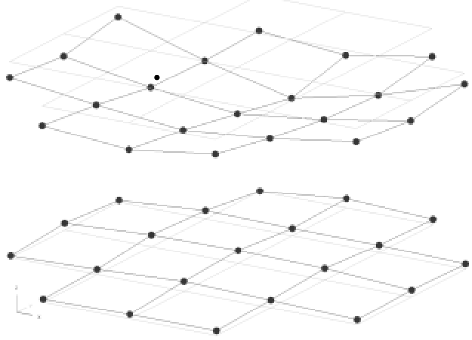
As shown in Table 3, the automatically paired EMA and FEA natural frequencies had considerable differences. This was because the FEA and EMA natural frequencies were paired by means of the highest MAC values, rather than the closeness in natural frequencies. However, it was expected that through model updating these relatively high differences could significantly be reduced and the MAC values could also be improved.

Table 3. Automatic mode pairing between the initial FE and EMA models

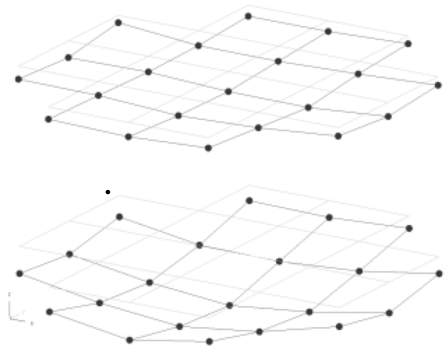
No	Initial FE model		EMA model		Difference [%]	MAC [%]
	Mode	Freq. [Hz]	Mode	Freq. [Hz]		
1	5	8.73	2	8.63	1.25	84.6
2	15	9.62	1	8.22	16.94	74.6
3	19	10.77	3	8.80	22.48	76.1
4	22	11.63	5	11.35	2.52	87.2
5	24	11.98	4	10.03	19.51	65.8



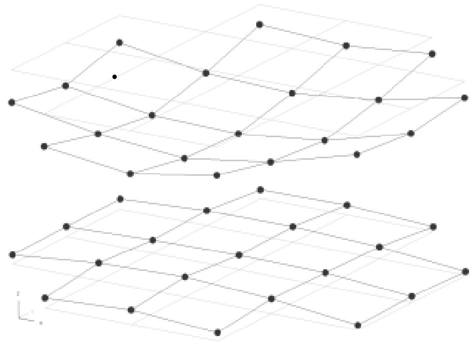
Undeformed shape



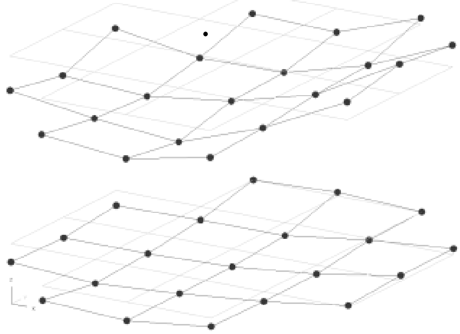
Mode 1 (f_1 = 8.22 Hz, ζ_1 = 3.81 %)



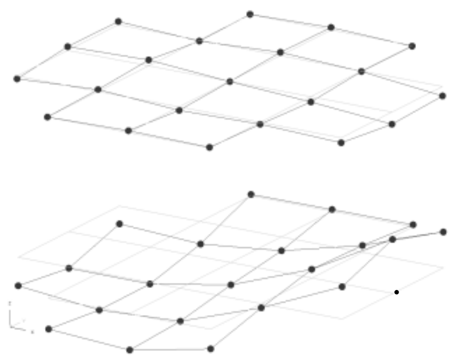
Mode 2 (f_2 = 8.63 Hz, ζ_2 = 2.06 %)



Mode 3 (f_3 = 8.80 Hz, ζ_3 = 2.27 %)



Mode 4 (f_4 = 10.03 Hz, ζ_4 = 1.96 %)



Mode 5 (f_5 = 11.34 Hz, ζ_5 = 2.05 %)

Figure 6. The first five estimated modal properties of the joint 2-level panel system

From the MAC matrix shown in Figure 7, the correlation between FEA and EMA mode shapes was also not good, and there are problems with spatial aliasing.

This problem could be, to a great extent, attributed to insufficient data points (measured DOFs) to discriminate between the different modes (Ewins, 2000). Indeed, the test grid consisted of only a pair of corner panels, where 21 test points were used to represent one panel.

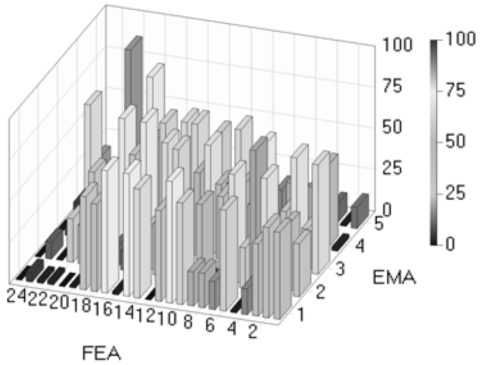


Figure 7. Isometric view of MAC matrix

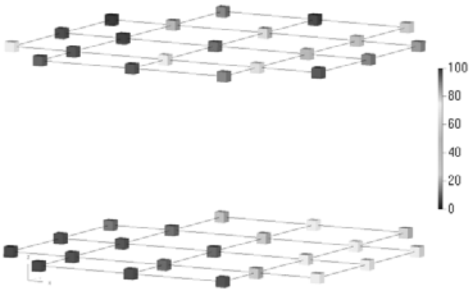


Figure 8. COMAC contour of the initial FE model using the test grid

COMAC values for the initial FE model is presented in Figure 8. As can be seen, COMAC values for most of the test points on the first floor show good correlation between FEA and EMA DOFs. However, some of the DOFs on the second floors are poorly correlated. Considering all of the findings from correlation analysis, the initial FE model was expected to be very much improved through the model updating.

In order to come up with an updated FE model, which is in satisfactory agreement with the experimental model, conducting sensitivity analysis is necessary (Widjaja, 2004). Here, a sensitivity analysis involving parameter which shares the same category and nominal value, called 'global' parameters, was conducted using FEMTools Model Updating Suite (DDS, 2000).

There were initially 195 global parameters divided into 10 categories. The categories and number of parameters can be seen in Table 4. The result of global sensitivity analysis for the joint two-floor FE model is presented in Figure 9, which shows the sum of normalized sensitivity values considered for all five 'responses' (natural frequencies). The numbering of the parameters shown in Figure 9 follows those in Table 4.

Tabel 4. Global parameters of the two-joint floor FE model used for sensitivity analysis

No	Parameter No.	Category	Applied to
1.	1 – 35	Dynamic mod. of concrete ($E_{c,dyn}$)	All structural elements
2.	36 – 70	Concrete density (ρ)	All structural elements
3.	71 –81	Cross-sectional area (A_x)	All beam and column elements
4.	82 – 92	Shear area in local y-direction(A_y)	All beam and column elements
5.	93 –103	Shear area in local z-direction	All beam and column elements
6.	104 – 114	Torsional stiffness (I_x)	All beam and column elements
7.	115 – 125	Bending moment of inertia (I_y)	All beam and column elements
8.	126 – 136	Bending moment of inertia (I_z)	All beam and column elements
9.	137 – 160	Membrane thickness (h)	All concrete slab elements
10.	161 – 195	Poisson's ratio (v)	All structural elements

DISCUSSION

It was revealed that the element cross-section (A_x), shear areas of (A_y and A_z) and torsional constant (I_x) of all the beams and columns are among the most insensitive global parameters. This finding can be seen for parameters 71 up to 114 in Figure 9. On the other hand, the concrete slab thicknesses and material density of the 1st and 2nd floor panels are found to be the most sensitive global parameters.

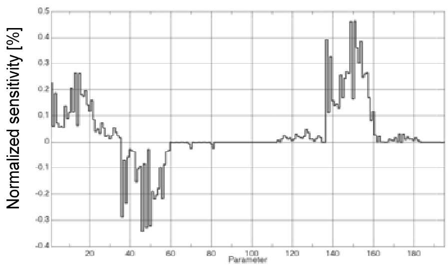


Figure 9. The sum of normalized sensitivity values of 'global' parameters

Furthermore, all the findings of global sensitivity analysis, in general, support the conclusions obtained from the local sensitivity analysis.

Table 5 summarizes the 'global' parameters of the 1st and 2nd floor levels used for model updating showing 12 categories of global parameters.

All five experimentally estimated natural frequencies and mode shapes from modal testing conducted on both corner panels were used as the reference response. For all cases of model updating, the pairing of analytical and experimental mode shapes was automatically conducted by FEMtools (DDS, 2000) by defining minimum MAC value for the paired mode.

As it was quite difficult to pair an EMA mode shape, an analytical mode was then paired to an experimental one if their MAC value was higher 0.50. Table 3 shows the paired modes with their natural frequencies difference. The automatic pairing of mode shapes was repeated automatically in each model updating iteration. This meant that MAC values were also automatically calculated and, hence, the pairing of mode shapes might be swapped between consecutive iterations.

Tabel 5. Summary of the 'global' parameters selected for model updating

No.	Structural element
Elastic dynamic modulus of concrete (GPa):	
1.	Concrete panels on the 1st floor
2.	Concrete panels on the 2nd floor
3.	Columns along the North and South sides of the building
4.	Upstand beams at the East and West sides of the building
Concrete density (kg/m^3):	
5.	Concrete panels on the 1st floor
6.	Concrete panels on the 2nd floor
7.	Upstand beams at the East and West sides of the building
Cross-sectional area (m^2):	
8.	Upstand beams at the West sides of the building
Bending moment of inertia (m^4):	
9.	Inner columns
10.	Upstand beams at the East and West sides of the building
11.	Columns along the North and South sides of the building
Poisson's ratio of concrete:	
12.	Panels 1 (at the corner of the 1st floor) and 13 (at the corner of the 2nd floor)

The initial FE model comprising a joint two-floor system was considered. It was found during initial updating exercises that the iteration process became very unstable and did not converge. As described by Widjaja (2004), the sensitivity-based model updating iterations converged when it satisfy the target function (CC_{abs} in FEMtools), which was defined as the rate of change between two iteration errors. CC_{abs} was set to 0.001.

It was also found that the pairing of FEA and EMA modes swapped from one FEA mode to another. Hence, CC_{abs} always changed whenever the pairing of modes was altered. This was because the automatic pairing of FEA and EMA modes was taken from paired modes which revealed the highest value of MAC.

As the going got tough, the target function was set to 0.005. Also, rather than having automatic pairing of FEA and EMA modes, predefined pairing was forced to be maintained during the updating process. It took more than 30 iterations to move CC_{abs} lower than 0.5% and more than 82 iterations to have the model updating iterations converged (see Figure 10).

The comparison of natural frequencies between the EMA and the initial and update FE model are presented in Table 6 and Figure 11.

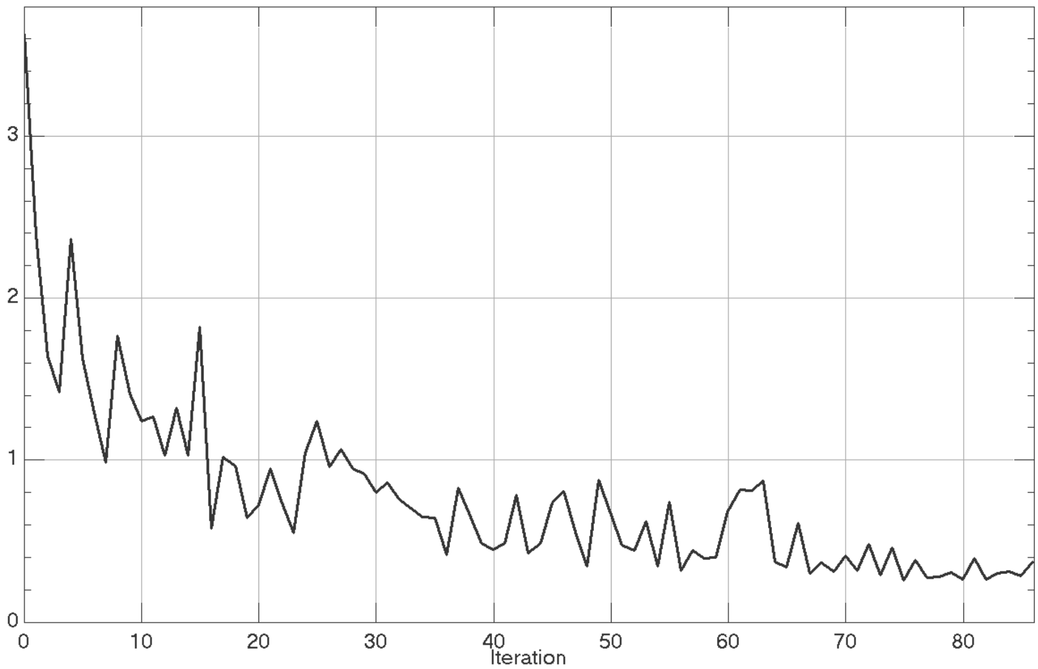


Figure 10. Model-updating iterations where vertical axis showing the value of CC_{abs} [%]

Tabel 6. Comparison of natural frequencies between EMA and the initial and updated FE models

No	EMA model		Initial FE model		Updated FE model	
	Mode	Freq [Hz]	Mode	Freq [Hz]	Mode	Freq [Hz]
1	1	8.22	15	9.62	1	8.22
2	2	8.63	5	8.73	5	8.63
3	3	8.80	19	10.77	8	8.80
4	4	10.03	24	11.98	16	9.98
5	5	11.34	22	11.63	22	11.25

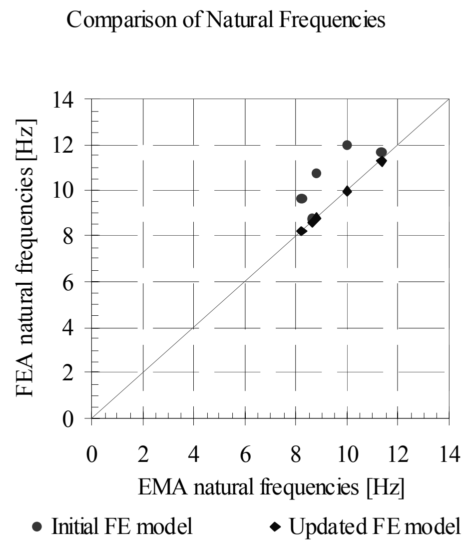


Figure 11. Comparison between EMA and initial and updated FEA models natural frequencies

It can be seen that, on average, the differences between analytically calculated and experimentally estimated natural frequencies are on average less than 0.6%, which is very small. Based on this finding, a significant improve-ment in the FEA model natural frequen-cies was achieved.

Full description of the MAC values of the updated joint floor model for each case is given in Figure 12. It can be seen, the MAC did not significantly improve after the updating. This means that the problem with spatial aliasing remains due to only small number of EMA DOFs were compared with the large number FEA counterparts.

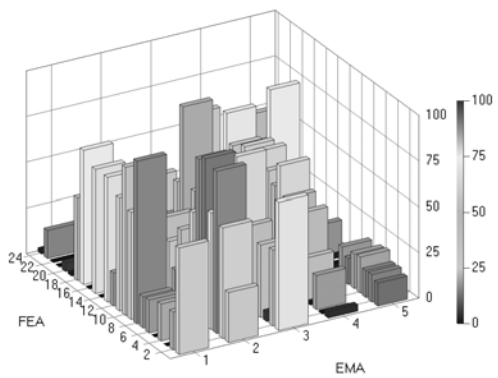


Figure 12. MAC values of the updated FE models

The COMAC diagram and contour of the updated joint two-floor FE model is presented in Figure 13. As can be seen the problem of very low COMAC values at the several test points on the 2nd floor panel does not exist. Also, the COMAC has generally very much improved.

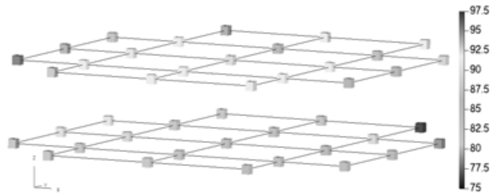


Figure 13. COMAC values of the updated FE models

Considering all these results, it can, therefore, be concluded that the updated FE model is an acceptable improvement of the initial FE model. The updated FE model was further verified against measurement data. The force time history was used to calculate time domain response at TP11 of the test grid. The analytically calculated time domain response, as can be seen in Figure 14, overlay well with the TP11 measured response. Therefore, based on this comparison, it can further be concluded that the updated FE model is a reliable analytical model of the two nominally identical real-life concrete building floors.

Conclusions

A formal procedure for conducting automatic FE model correlation and updating of two adjacent floor levels of nominally identical layout against incomplete experimental modal data (natural frequencies and mode shapes) was successfully implemented.

The success of automatic model updating was possible after good initial FE models were obtained by manual updating based on trial and error.

Therefore, combining manual and automatic updating is essential for a successful FE model correlation and updating. Furthermore, by having a reliable updated FE model, further studies, such as, simulations of vibration transmission between two adjacent floor levels can be performed with confidence.

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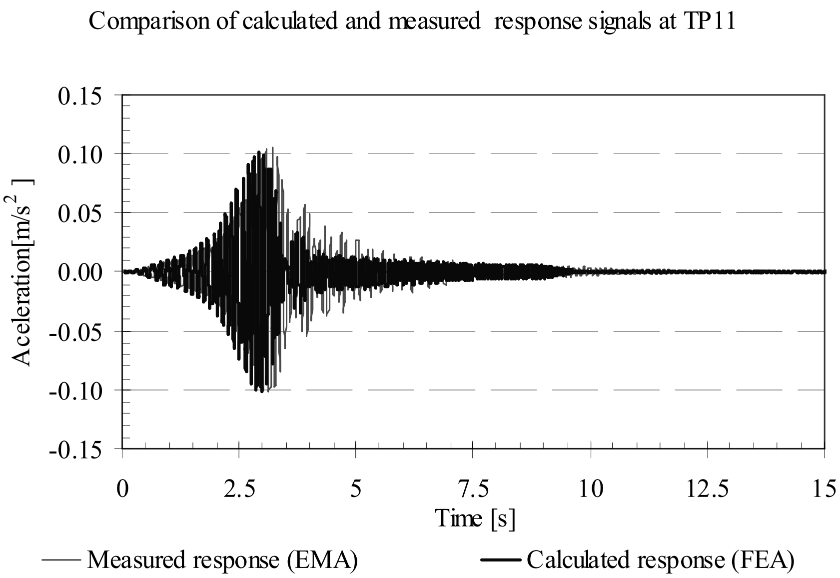

Figure 14. Comparison between measured and calculated time domain response at TP11

The number and type of FE modeling parameters used for model updating were determined based on sensitivity analysis. Sensitive parameters are those that could cause considerable change in natural frequencies and mode shapes of the FE model.

Floor mass and stiffness properties, such as modulus of elasticity, concrete density and slab thickness, were among the most sensitive parameters. Next, among sensitive parameters were also the bending stiffnesses of beams and columns. On the other hand, axial stiffnesses of columns were among the most insensitive parameters, as they had unnoticeable effect on dynamic properties of the FE model simulating vertical bending of floors.

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