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Improving FE models of a long-span flat concrete floor using natural frequency measurements

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Abstract

The paper identifies an appropriate FE model for determining the dynamic characteristics of a long-span flat concrete floor using natural frequency measurements. The Cardington concrete building was selected for the study because it represents a popular form of concrete construction. The natural frequencies of the floors were measured. Several FE models of the floor are considered and the models are refined based on the comparison between numerical predictions and the frequency measurements. It is concluded that a floor-column model provides the most appropriate representation of the actual structure.

1. Introduction

Long-span flat slabs supported by columns are widely used for floors in offices, shopping centres and airport terminals. The use of this type of structure can lead to a serviceability problem due to vibrations produced by people walking and this should be considered in design. However, the dynamic behaviour of this type of floor is not well understood. The objective of this study is to identify an appropriate FE model for this type of floor, which can be used to study its dynamic behaviour.

A seven-storey in-situ concrete building has been constructed inside the BRE Cardington Laboratory as a part of the European Concrete Building Project (ECBP). It was designed as an office building and in situ concrete was chosen because it is the most popular form of concrete construction [1].

The building consists of seven storeys of 3.75 m each in height, giving a total height of 26.25 m. The building has three bays of 7.50 m constituting a width of 22.50 m and four bays of 7.50 m making a length of 30.00 m. The building has been designed to Eurocode 2. The building was built on pad foundation supported on the existing floor. The cross-sections of the columns are kept constant throughout the height of the building. High strength concrete C85 is used in the first three storeys and C37 concrete is used from the fourth floor up to the roof level. In the absence of cross walls or diaphragms, the lateral stiffness of the building is enhanced by steel cross bracing members. The building is shown in Fig. 1.

The building floors have been designed as reinforced concrete flat slabs and cast in C37 concrete, which is typical for this type of construction. The flat floor slabs are 0.25 m thick with each slab having a different arrangement of reinforcement steel. The floors have been designed to carry an imposed load of 2.5 kN/m^2 instead of the usual 4.5 kN/m^2. The flat slab construction offers significant advantages to contractors in ease of

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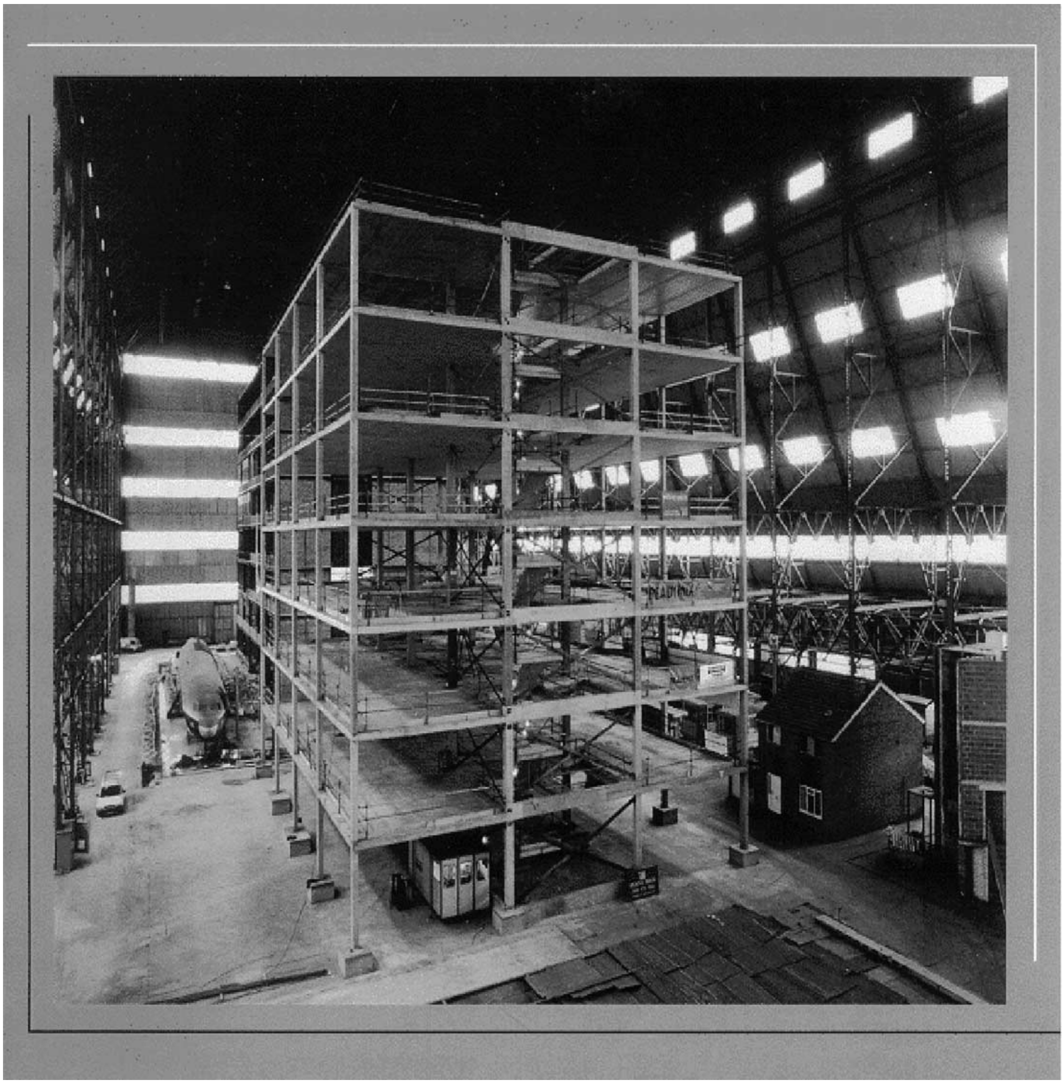

Fig. 1. The seven-storey in situ flat slab concrete building in the BRE Cardington laboratory.

construction and to building owners and users, and flexibility in fitting out buildings.

The structure is designed and constructed as realistically as possible, so the floors have voids for stairs, lift shaft and services. The layout of a typical floor plan and the elevation of the building are shown in Figs. 2 and 3 respectively.

Dynamic tests on the floors were conducted by Building Research Establishment Ltd. The tests involved monitoring the acceleration of the centre of each floor area in response to a heel-drop. The response was then converted to an autospectrum using an FFT procedure and the dominant natural frequency identified, (i.e. many spectra showed several modes although one mode would dominate the response at any one position). Measurements were taken from 11 locations in each floor and throughout all seven floors. This type of testing was undertaken as it is both simple and quick and provides data for comparing the various floors and bays. The test locations are indicated in Fig. 2 and the measured frequencies are listed in Table 1. The measurements provided a basis for evaluating the quality of different FE models. Consequently, FE analysis of several commonly used models is conducted, and the numerical and experimental results are compared. This leads to refining the FE models and indicates that a floor-column model should be used for studying the dynamic behaviour of a long-span flat floor supported by columns.

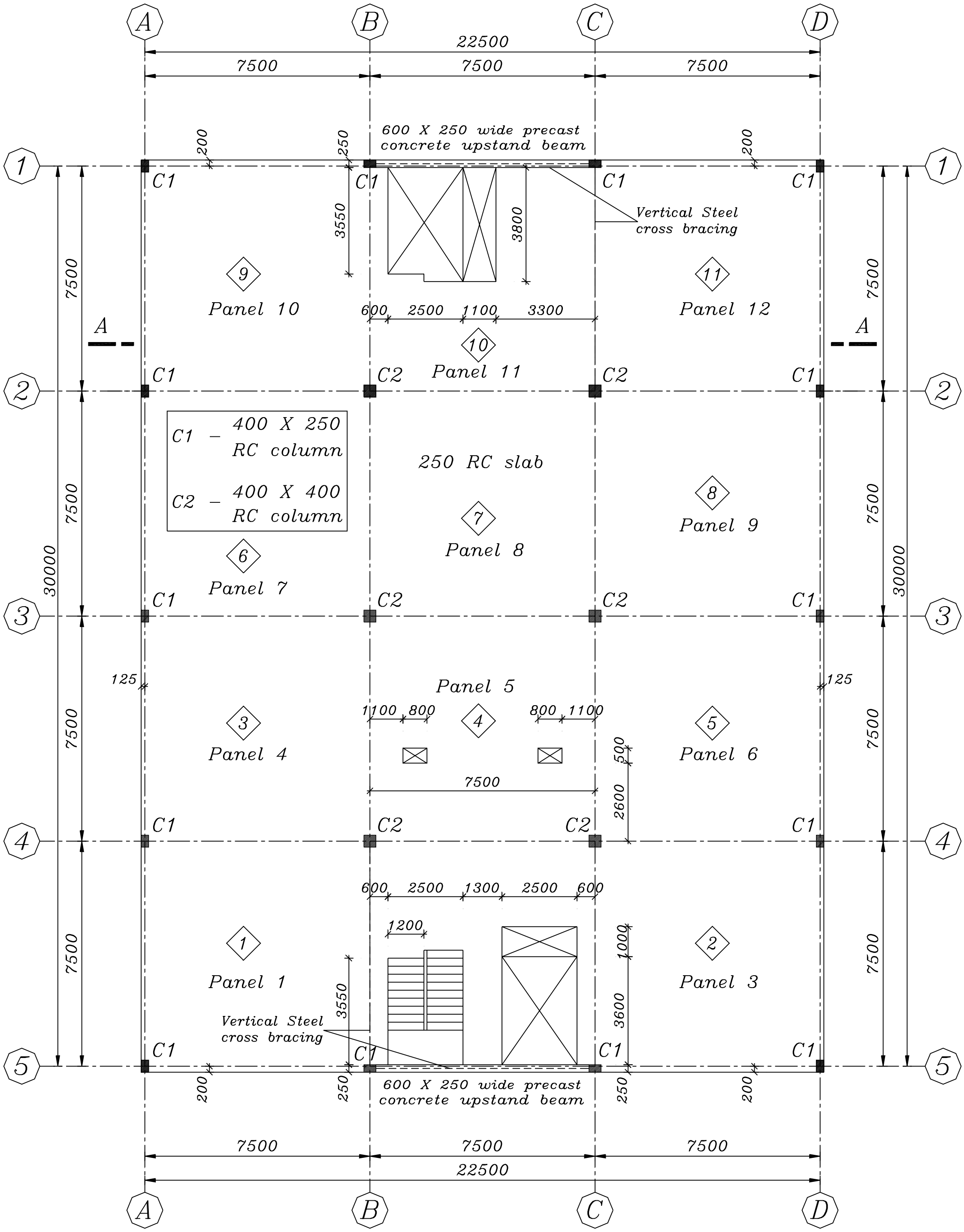

Fig. 2. The plan of a typical floor, the panel numbers and the test locations.

The numerical and experimental studies on the floor have been conducted independently. The improvement of the numerical models is based on the comparison between the predictions and measurements and engineering

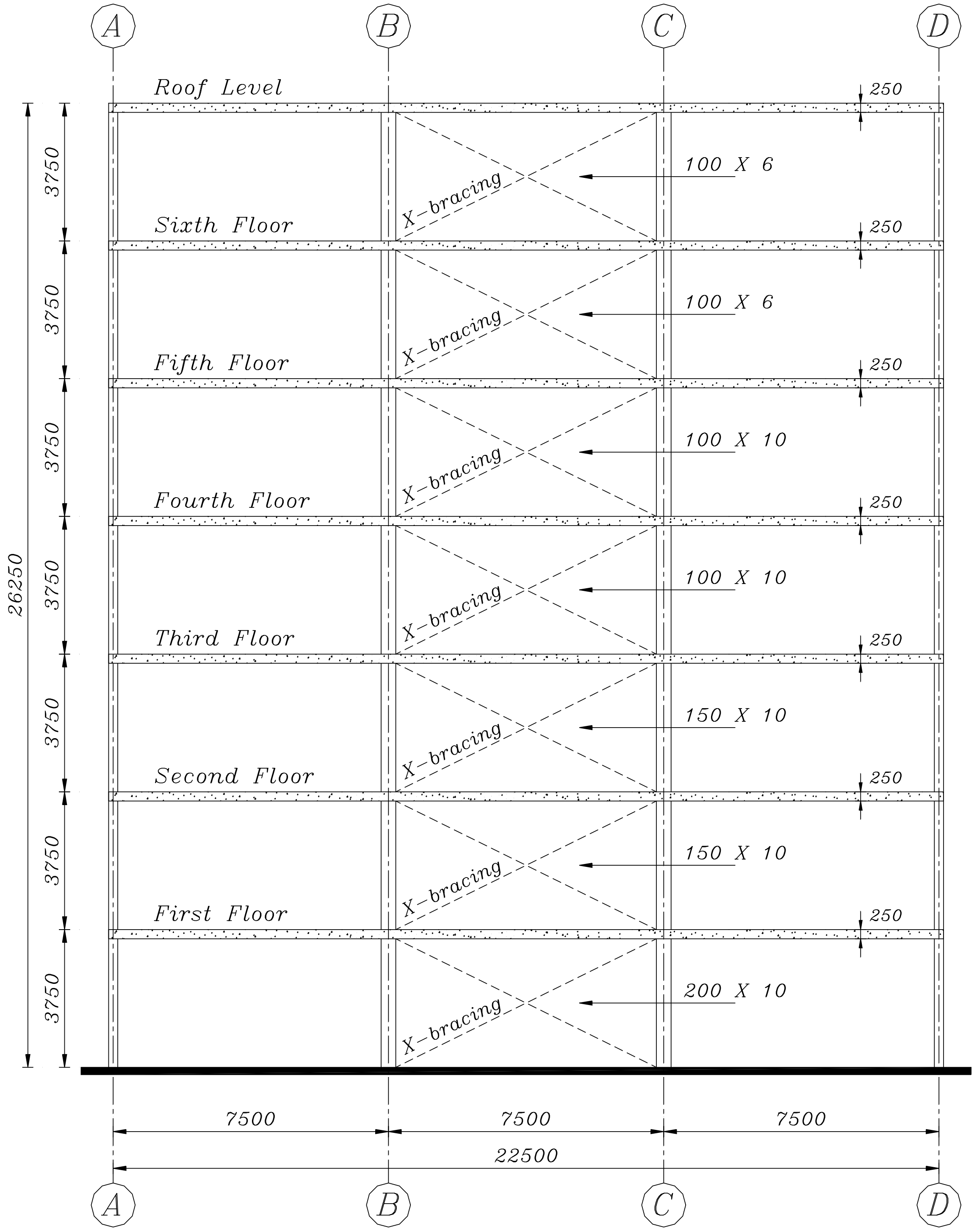

Fig. 3. The elevation (sec. A–A).

judgement. Similar work, where both numerical and experiment studies are concerned, can be found in Refs. [2,3]. Theoretical studies on examining the frequencies of continuous multi-bay floors were reported in Refs. [4,5].

Table 1
Measured frequencies of all building floors in Hz

Panel no.	Floor no.						
	1	2	3	4	5	6	7
	$E_c = 30.5$ (GPa)	$E_c = 35.5$ (GPa)	$E_c = 38$ (GPa)	$E_c = 38$ (GPa)	–	–	–
Experimental results							
1	8.54	8.54	8.54	8.30	8.54	7.57	7.57
2	–	–	–	–	–	–	–
3	8.79	8.54	8.79	8.79	8.06	8.06	7.57
4	9.77	9.28	10.25	9.52	9.28	9.28	8.79
5	11.96	11.72	11.96	11.96	11.47	10.74	10.74
6	9.52	9.52	9.77	9.77	9.28	8.79	8.54
7	9.52	10.01	9.28	9.77	9.77	9.28	9.28
8	11.96	11.96	11.72	12.21	11.47	10.74	10.74
9	9.52	9.28	9.52	9.77	9.28	9.28	8.79
10	8.79	8.54	8.54	8.30	8.06	7.57	7.57
11	11.23	10.74	10.74	11.23	10.50	10.01	10.01
12	9.03	8.54	8.54	9.03	8.54	8.06	8.30

2. FE modelling of the floor

Several models that include different structural components are used to represent the floor of the test building at Cardington. The experimental data from the floor in the second storey is considered in the modelling. The FE program LUSAS [6] is used for this investigation. *3D flat thin shell elements* (*QSI4*) are used for

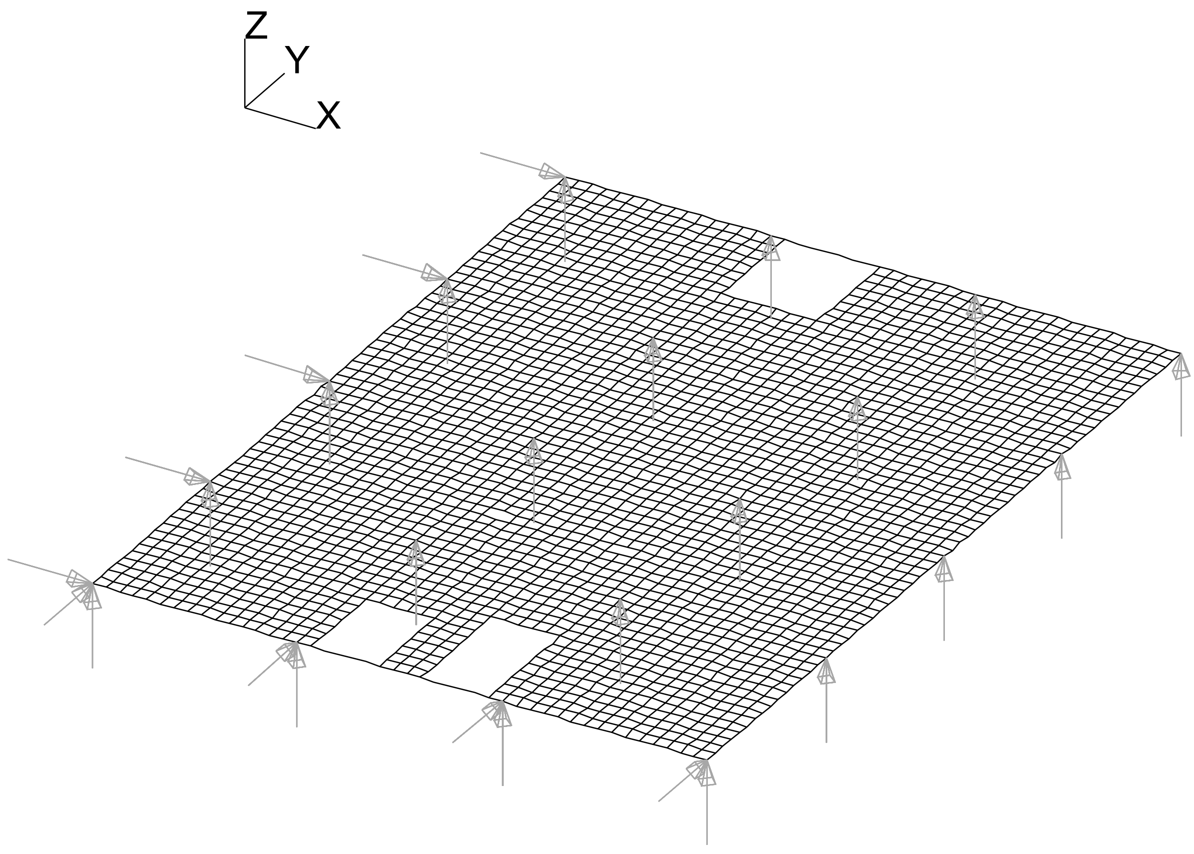

Fig. 4. The pin supported floor model.

modelling the floor slab. These elements take into account both membrane and flexural deformations. The *3D thick beam elements* (*BMS3*) are used for representing columns and beams. An element of this type can resist axial stretching, bending and transverse shear force in the three directions. For all of the FE models, necessary constraints in the floor plane are provided to prevent rigid body movements.

The FE models of the floor considered in the study include:

- A floor model with pinned supports from columns.
- A floor model with fixed supports from columns.
- A floor-column model.
- A floor-column model considering the effect of reinforcement in columns.

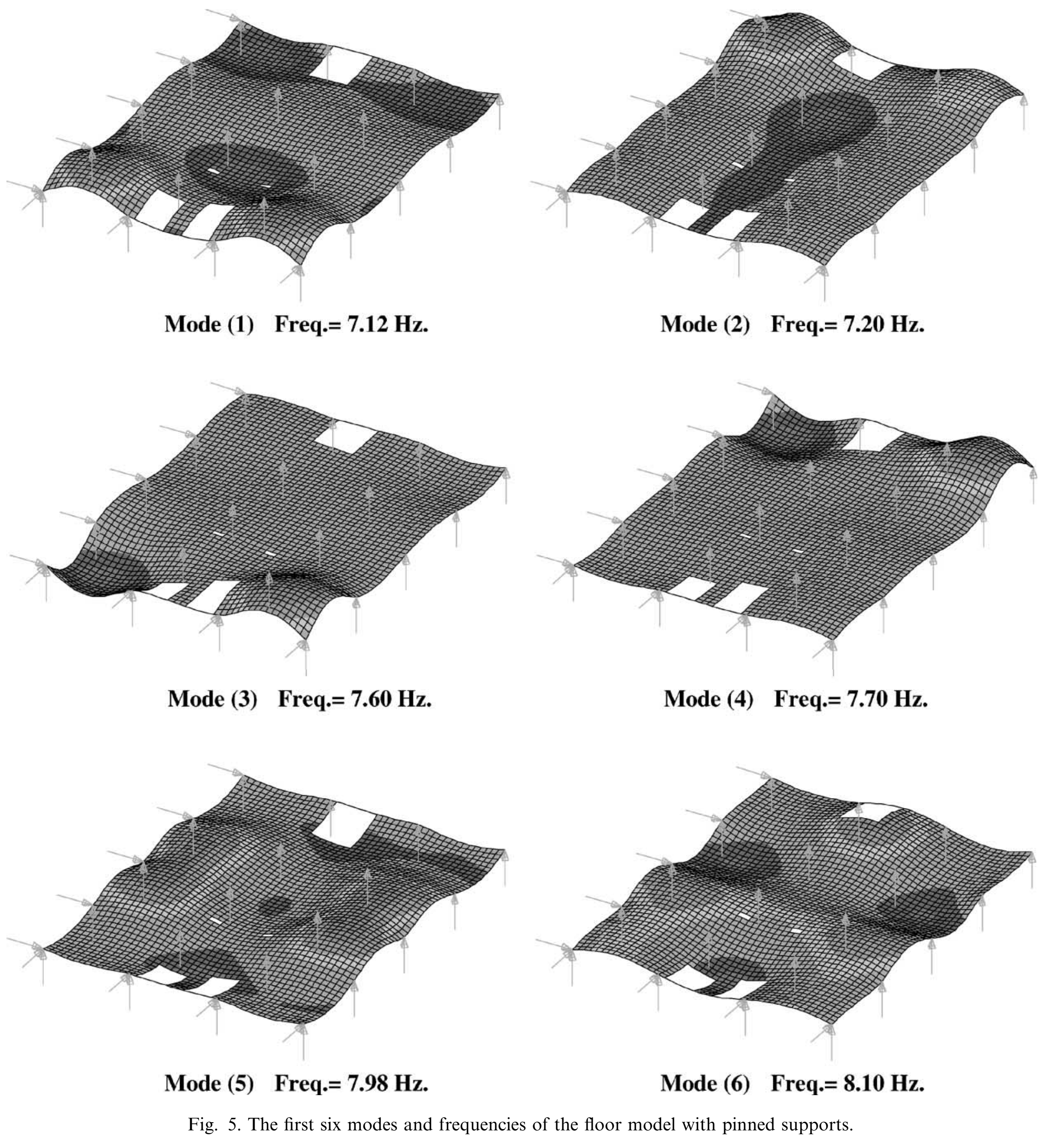

Fig. 5. The first six modes and frequencies of the floor model with pinned supports.

Initially the effect of mesh sizes on the dynamic behaviour was studied. Three different meshes were considered but they had a negligible effect on the natural frequencies, although they affected the appearance of the mode shapes. Thus a fine mesh (see Fig. 4) was adopted.

The basic data used in the modelling was

the thickness of the floor	25 cm,
the cross-sections of columns	40×25 cm and 40×40 cm,
the Young's modulus	35.5 GPa,
the Poisson ratio	0.20,
the material density	2400 Kg/m^3.

The natural frequencies obtained from analysis and experiment will be compared for each FE model considered. It is important to identify the correct modes for comparison. The measurements were taken from heel drop tests at the centre of each panel. As a result, the test generated the mode with the maximum response at the centre of the panel. When vibration modes are calculated, the maximum relative displacements are found out in order to compare with the experimental measurements.

It is recognised that the measurement of the mode shapes would have provided further information for comparison with theory. However, mode shape measurement for each mode throughout the building would require a far more comprehensive test programme, and it was thought that much could be gained using the measured frequencies.

2.1. A floor model with pinned supports from columns (model 1)

In the floor model with pinned supports the columns are assumed to be completely stiff in the vertical direction but to provide no rotational restraints to the slab. Therefore, they are modelled as vertical pinned supports that are commonly considered in practice. The FE mesh and the boundary supports of the floor are shown in Fig. 4. The calculated first six natural frequencies and the mode shapes are summarised in Fig. 5.

The comparison between the natural frequencies of the 12 modes extracted from the numerical analysis and the measurements is summarised in Table 2.

Table 2 shows that the calculated natural frequencies of the pin supported floor model are consistently lower than the measured values. This is probably due to the assumption that the columns do not provide any rotational restraint. Thus, the slab-column joints are not sufficiently rigid and the pin supported floor model has less stiffness than the real floor. This assumes that the mass of the floor is modelled accurately, which is reasonable for this experimental building where quality control was closely monitored. The ratios of numerical to experimental results change between 75% and 91% for the first 12 modes.

Table 2
Comparison between FE results of model 1 and measurements

Mode no.	Pinned floor model (freq. (Hz))	Measurements (freq. (Hz))	Ratio % (FE result/measurements)
1	7.12	8.54	83.39
2	7.20	8.54	84.34
3	7.60	8.54	88.95
4	7.70	8.54	90.12
5	7.98	9.28	85.99
6	8.10	10.74	75.42
7	8.75	9.52	91.95
8	8.82	10.01	88.14
9	9.76	–	–
10	10.21	–	–
11	10.50	11.72	89.55
12	10.94	11.96	91.50

2.2. A floor model with fixed supports from columns (model 2)

Since the floor is less stiff using the pin supported floor model, a floor model with fixed supports from the columns is considered. In this model columns provide complete fixed supports, both translational and rotational.

The boundary conditions of this model and the corresponding results are shown in Fig. 6. In comparison with the first model, it can be seen that there are no significant changes in the mode shapes of the floor, but the natural frequencies of the floor have increased. A similar comparison is considered in which the FE and the experimental results are given in Table 3.

Table 3 shows that the natural frequencies of the fixed floor model are higher than the measurements. This indicates that the slab-column joints are too rigid. Consequently, the floor model with fixed supports is stiffer than the real floor. The ratios of numerical to experimental results range from 95% to 112% for the first 12 modes and are greater than 1.0 for nine of the 10 modes compared.

2.3. A floor-column model (model 3)

The floor model with pinned supports is less stiff and the floor model with fixed supports is stiffer than the actual floor. This observation indicates that a floor-column model may be appropriate and this is considered here.

The floor-column model consists of the flat slab floor and the full-length columns that connect to the floors from the upper and lower storeys. The upper and lower columns have the same height of 3.75 m. The far ends of

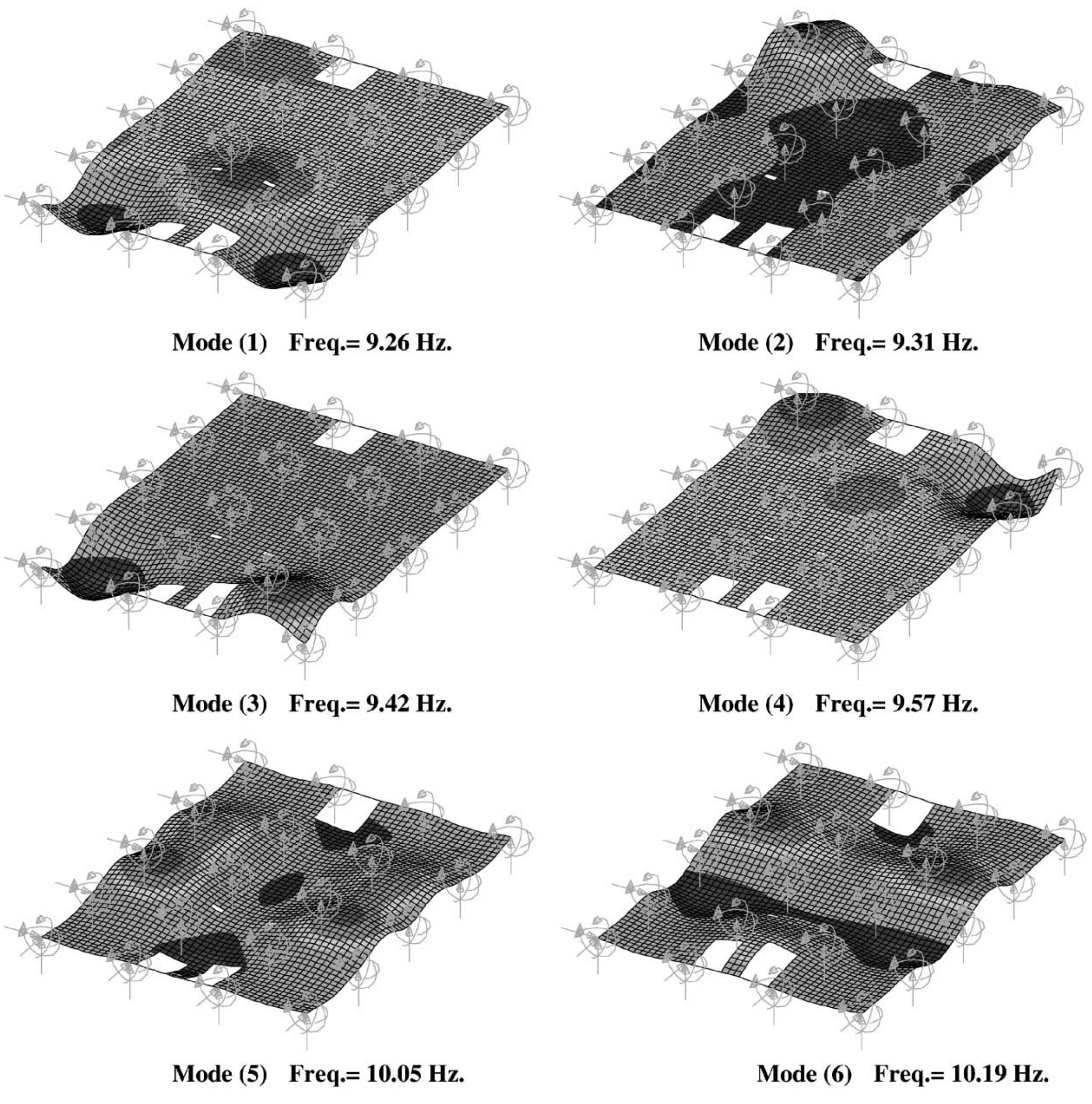

Fig. 6. The first six modes and frequencies of the floor model with fixed supports.

the columns are assumed to be restrained against both translations and rotations. The model and the boundary conditions are presented in Fig. 7 and the calculated natural frequencies and the mode shapes are summarised in Fig. 8.

A comparison between the natural frequencies of the 12 modes extracted from the numerical analysis and the measurements is given in Table 4.

Table 4 shows that the calculated frequencies are close to the measured ones. The ratios of the predicted to experimental results vary from 94% to 101% for the first 12 modes. The comparison indicates that the floor-column model is more appropriate than the floor models with either pinned or fixed supports for studying dynamic behaviour of a long-span flat floor supported by columns.

2.4. A floor-column model considering the effect of reinforcement in columns (model 4)

Since the flat slab floor supported by columns is a relatively simple structure and the basic input data are

Table 3
Comparison between FE results of model 2 and measurements

Mode no.	Fixed floor model (freq. (Hz))	Measurements (freq. (Hz))	Ratio % (FE result/measurements)
1	9.26	8.54	108.49
2	9.31	8.54	109.04
3	9.42	8.54	110.33
4	9.57	8.54	112.00
5	10.05	9.28	108.25
6	10.19	10.74	94.90
7	10.37	9.52	108.94
8	10.56	10.01	105.46
9	11.54	–	–
10	11.57	–	–
11	11.90	11.72	101.51
12	12.44	11.96	103.99

thought to be correct, it should be possible to model it accurately. The comparison shown in Table 4 indicates that the prediction is close to the measurements, but a little more flexible than the actual structure. This may be due to the exclusion of the effect of reinforcement in the structure. Therefore, the effect of reinforcement in columns on the dynamic behaviour of the floor is considered.

The consideration of the effect of reinforcement in columns in the analysis is equivalent to enlarging the Young's modulus or the second moment of area of the columns. When the ratio of the steel area to the concrete area is assumed at 2%, the effective Young's modulus is 1.27 times the original value for columns. Based on the previous floor-column model, the effective Young's modulus is used for columns instead of the original one. This model thus considered the effect of the reinforcement on the dynamic behaviour of the floor.

Table 5 provides a comparison between the measurements and the predicted natural frequencies of the floor-column model considering the effect of reinforcement in columns. As expected the predicted frequencies increase in comparison with those obtained from the last model. The ratios of the predicted to measured frequencies range from 95% to 102%. Comparing the predicted results in Tables 4 and 5, it can be seen that the consideration of the effect of reinforcement in columns improves the quality of the floor-column model although the change is not significant.

2.5. Summary of floor models

Four different floor models are considered in this investigation. The model is gradually refined based on

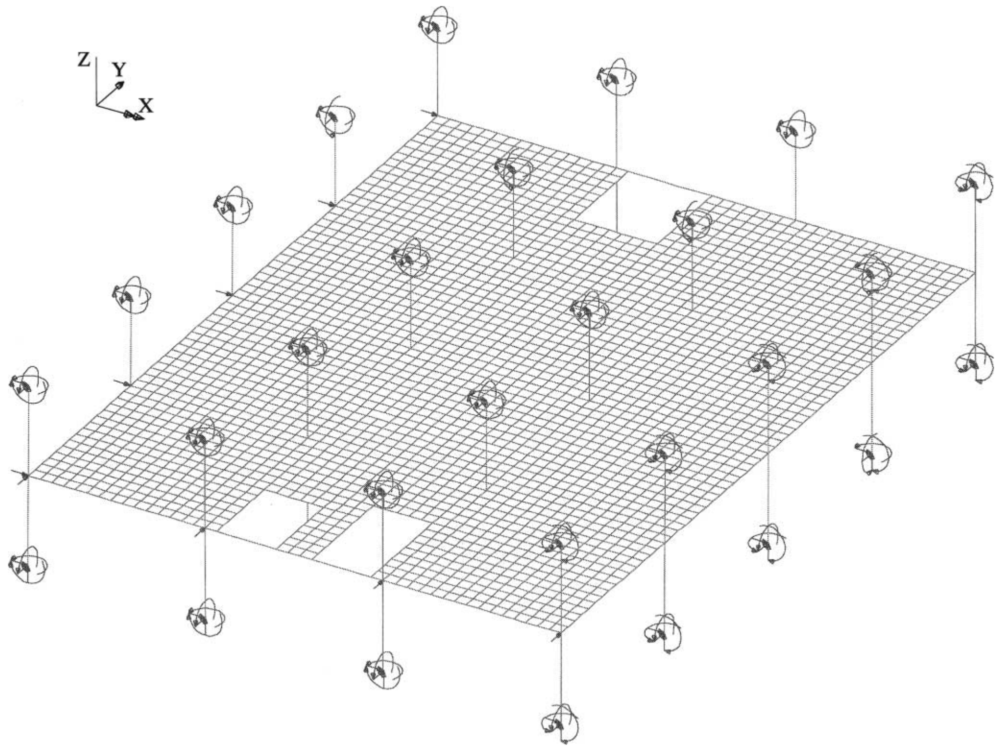

Fig. 7. The floor-column model.

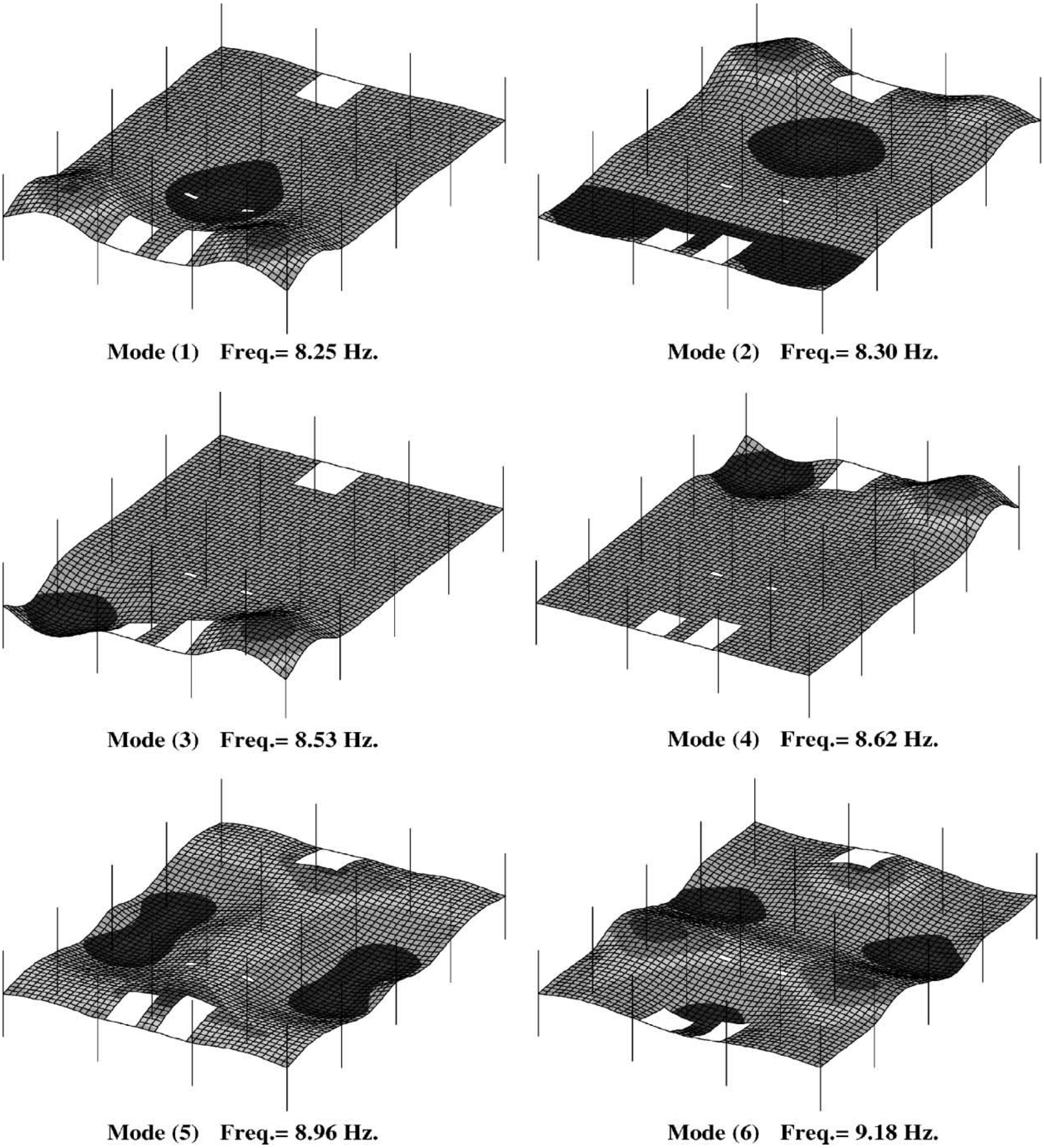

Fig. 8. The first six modes and frequencies of the floor-column model.

the comparison between the predictions and the corresponding measurements.

The predicted natural frequencies of the four models and the corresponding measurements are summarised in Table 6.

The maximum differences in the range of ratios of the numerical to experimental frequencies for the first 12 modes are summarised in Table 7. It can be concluded that the floor-column model provides the most appropriate representation of the actual structure.

If only one or two modes were considered and the Young's modulus were updated based on the floor model with either pinned or fixed supports, it would give a good comparison between the first one or two pre-

Table 4
Comparison between FE results of model 3 and measurements

Mode no.	Floor-column model (freq. (Hz))	Measurements (freq. (Hz))	Ratio % (FE result/measurements)
1	8.25	8.54	96.61
2	8.30	8.54	97.17
3	8.53	8.54	99.94
4	8.62	8.54	100.95
5	8.96	9.28	96.56
6	9.18	9.28	98.88
7	9.41	9.52	98.88
8	9.73	10.01	97.18
9	10.72	–	–
10	10.76	10.74	100.15
11	11.04	11.72	94.18
12	11.56	11.96	96.65

Table 5
Comparison between FE results of model 4 and measurements

Mode no.	$E_{c\ floor} = 35.5$ GPa, $E_{c\ Column} = 45.0$ GPa (freq. (Hz))	Measurements (freq. (Hz))	Ratio % (FE result/measurements)
1	8.38	8.54	98.08
2	8.42	8.54	98.63
3	8.64	8.54	101.22
4	8.73	8.54	102.26
5	9.09	9.28	97.94
6	9.30	9.28	100.26
7	9.53	9.52	100.11
8	9.84	10.01	98.26
9	10.83	–	–
10	10.89	10.74	101.39
11	11.13	11.72	94.92
12	11.67	11.96	97.58

Table 7
The differences of the range of ratios of numerical to measured frequencies

Model no.	Ratio % (FE/measurements)	Maximum differences
1	75–91	16%
2	95–112	17%
3	94–101	7%
4	95–102	7%

dicted and measured frequencies. However, this kind of model updating may lead to an incorrect conclusion. Nevertheless, the accuracy of the basic input data should always be considered.

3. Conclusions

Four different FE models of a long-span flat floor were investigated in conjunction with experimental measurements of natural frequencies. The models were gradually refined, based on the comparison between the numerical predictions and the corresponding measurements. It is concluded from this study that

1. The floor-column model gives the most appropriate representation of the actual structure for studying the dynamic behaviour of long-span flat floors supported by columns.
2. The different models used in this study give different frequencies but the mode shapes are similar in a global sense.
3. Simply updating the first model by increasing the E value might provide a reasonable match between the first few measured and calculated frequencies,

Table 6
Comparison between FE results of four models and measurements

Mode no.	Pinned floor model (1) (freq. (Hz))	Fixed floor model (2) (freq. (Hz))	Floor-column model (3) (freq. (Hz))	Floor-column model (4) (freq. (Hz))	Measures (freq. (Hz))
1	7.12	9.26	8.25	8.38	8.54
2	7.20	9.31	8.30	8.42	8.54
3	7.60	9.42	8.53	8.64	8.54
4	7.70	9.57	8.62	8.73	8.54
5	7.98	10.05	8.96	9.09	9.28
6	8.10	10.19	9.18	9.30	9.28
7	8.75	10.37	9.41	9.53	9.52
8	8.82	10.56	9.73	9.84	10.01
9	9.76	11.54	10.72	10.83	–
10	10.21	11.57	10.76	10.89	10.74
11	10.50	11.90	11.04	11.13	11.72
12	10.94	12.44	11.56	11.67	11.96

but this could fail to model the whole system correctly.

The experimental data were obtained quickly using a simple test scheme that could be used on a wide range of structures. However the measurements provided adequate information for the purposes of this project.

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