

Forced vibration testing of a thirteen storey concrete building

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ABSTRACT: Testing of structures to understand their behaviour under seismic conditions can provide an important source of information for safe and economical design. The need for testing the behaviour of full scale structures under dynamic loads stems from the fact that laboratory scale structures cannot account for all complexities involved. This paper describes forced vibration testing of a 13 storey reinforced concrete building having central lift core, shear walls and flat slabs, to find out its dynamic characteristics. Experiments have been carried out using the shakers and sensors within the NZNEES@Auckland Mobile Field Laboratory. Different positions of the shakers and sensors has been tried to determine optimal response of the structure. The field observations have been compared with finite element computer model. An effort has been made to synchronize a computer model with the field observations. It is emphasized that response of complex structural systems may be understood better by using the presented experimental and analytical tools.

1 INTRODUCTION

The dynamic behaviour of the structures under the seismic excitation is of major interest to structural engineers. Prior to occurrence of an earthquake, it is important to determine the structural characteristics such as natural frequencies, mode shapes and damping, so as to correctly estimate the response of the structure under resonating conditions (Beck 1980). However much of the research in structural dynamics and earthquake engineering has been confined to laboratory scale structures and cannot account for the complexity of the in situ structures such as the influence of non structural components, effects of different environmental conditions, and soil structure interactions, to name just a few.

The full scale dynamic testing results represent the information of the structures with correct boundary conditions and eliminate any need for scaling. The results from full scale testing can also provide a benchmark to calibrate structural models and help in developing new mathematical models capable of representing the true behaviour of structures. Dynamic identification of full scale structures such as concrete and masonry buildings, towers and bridges have been done by many researchers under different loading conditions, e.g. wind, earthquake, traffic etc. (Ellis 1996; Li et al. 2004; De Sortis, et al. 2005; Chen and Zhou 2007). Because of the advantages associated with full scale testing, many structures have been equipped permanently with monitoring systems capable of measuring their responses under actual service loading and earthquake excitations (Skolnik, et al. 2006). Efforts have also been made to compare the results of laboratory scale and full scale structures e.g.(Okada and Ha 1992).

Full scale testing can be done by performing ambient vibration tests or forced vibration tests (Salawu and Williams 1995). In ambient vibration tests, the excitation is not under the control and is usually considered as a stationary random process, which means that response data from the structure alone can be used to estimate the dynamic parameters. The increasing popularity of this method is due to the fact that no forcing machinery is required. Ambient excitation can be from sources such as wind, pedestrian or vehicular traffic, earthquakes, waves or similar. For very large and massive structures, ambient excitation is often the only practical choice. Structural identification through ambient

vibrations has been successful in numerous cases (Ivanovic, et al. 2000; Ventura, et al. 2003). However, ambient vibration testing has some important drawbacks mostly associated with the lack of information on the actual forcing. Most of the ambient identification procedures assume a white noise excitation, which is always only a reasonable approximation at best, and can be wrong at worst, leading to imprecise or wrong system identification results. A considerable degree of non linearity exhibited by real structures can also complicate the analysis in these tests.

In case of the forced vibration testing, the input excitation to the structure is provided by properly designed excitation systems, which entails application of a known force at particular frequencies or frequency bands of interest (Causevic 1987; De Sortis, et al. 2005). This method is based on the fact that if the loading on the structure and resulting responses are known, then the structural characteristics can be more unambiguously determined. These types of tests also have the advantage of the achieving larger signal to noise ratios in the response measurements (Salawu and Williams 1995).

As the experimental setup for a remote site involves mobilization of large resources, e.g. movement of heavy equipments like shakers or exciters, it is advisable to conduct a preliminary experimental investigation of a structure before the final tests by using small exciters instead of large ones. This will be helpful for planning further testing, e.g. deciding positioning of large exciter in the structure, particular force vibration method to use and frequencies of interest. It can also reduce the number of surprises encountered during the experimentation. Another challenge associated with the forced vibration testing of full scale structures is the amount of force required to produce appreciable excitation to the structure. This is related to the size of the building and the shaker/exciter. This paper describes the use of small shakers to detect the dynamic characteristics of a 13 story building. In the sections to follow, first the description of the structure, overview of the equipment used and testing plan is documented. Then the finite element model (FEM) of the structure is explained, and finally, the experimental results are compared with FEM model.

2 DESCRIPTION OF THE STRUCTURE AND TESTING PROGRAMME

The building selected for the experiment is a 13 storey tower block (Fig. 1) that is a part of the Engineering School at the University of Auckland. The building was designed in 1964 according to NZS 1900 and is separated from adjoining buildings by seismic gaps. The building has a total height of 40.5 m and is used as an office building for academic staff. The structural system (Fig. 2) of this building mainly consists of shear walls as a core and concrete columns around the perimeter.



Figure 1 South and west face of the engineering building

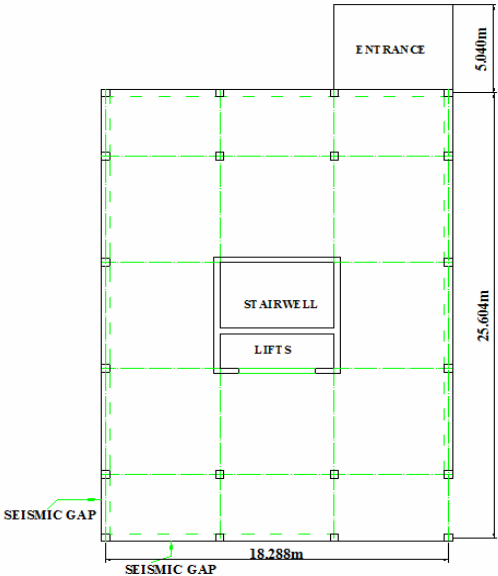


Figure 2 Structural system of the engineering building at level-4

The thickness of all floor slabs is 200 mm except the 14th which has a thickness of 120 mm. The slabs from level 5 to 13 are of a flat plate type and the column dimensions are 0.457 x 0.457m in these storeys. The core wall has a thickness of 305mm and contains two lifts and stairwell. The building has a small penthouse within the core on the 14th storey, which contains a machine room and water tank.

Experiments have been carried out using the shakers and sensors within the NZNEES@Auckland Mobile Field Laboratory. The data acquisition system used in this experiment comprised eight uni-axial accelerometers, one desktop computer fitted with NI-DAQ 6024E data acquisition card and one laptop fitted with NI-DAQ 6036 E data acquisition card. The desktop was used to control the operations of the shaker and the laptop was used to acquire the data from eight channels. Data were sampled at 200 Hz using Matlab Data Acquisition Toolbox (Mathworks 2005). Two long stroke APS Dynamics ElectroSeis Model 400 shakers (APS Dynamics 2008) were used to conduct the forced vibration tests. The shakers and data acquisition system are shown in Figure 3 & 4. The shakers were mounted in a position to deliver horizontal force to the structure. The two shakers were mounted on 13th floor of the building and were used in phase to provide a joint force of approx. 0.80 kN. Low frequency amplifiers were used to provide armature drive power to the shakers. The shakers and accelerometers can be located on the structure where natural vibration of modes gives maximum response.



Figure 3 Two long stroke APS Dynamics shakers and an accelerometer



Figure 4 Data acquisition system

Because of low force levels and a relatively large size of the building, it was decided to use different positions of the two shakers so as to get translational and torsional responses separately. It was also decided to use a stepped sine forcing so as to get a steady state response of the structure. The following was the test schedule:

2.1 Test No.1

Test No. 1 forced the structure in the North-South direction to excite translational responses. The two shakers were placed within the core of the structure, close to its shear centre, and the forcing frequencies were ranging from 1.5 Hz to 3.5 Hz with a step of 0.1 Hz. The setup of the accelerometers and the shakers is shown in Figure 5. To determine the mode shapes, eight accelerometers were also placed in each of the top eight stories.

2.2 Test No.2

Test No. 2 forced the structure in the translational direction in the East-West direction. The two shakers were placed within the core of the structure as shown in Figure 6. The forcing frequencies were same as of Test No. 1. Mode shape was also determined by placing the accelerometers in top eight stories.

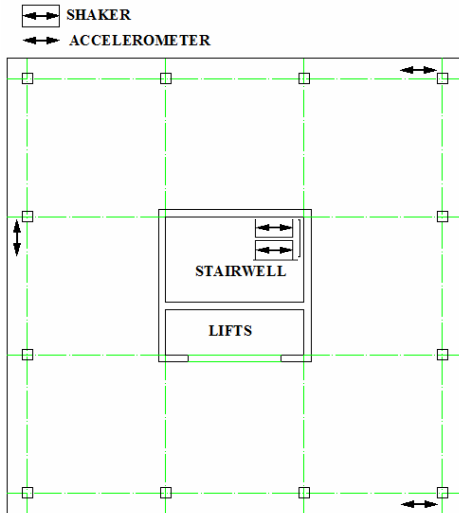


Figure 5 Position of shakers and accelerometers for Test No. 1

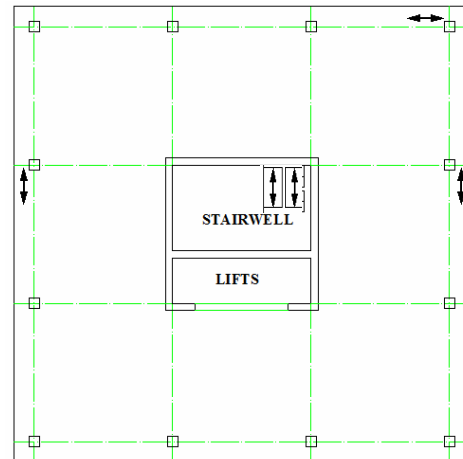


Figure 6 Position of shakers and accelerometers for Test No. 2

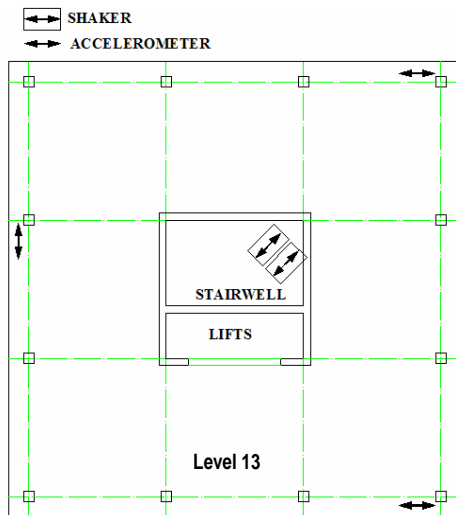


Figure 7 Position of shakers and accelerometers for Test No. 3

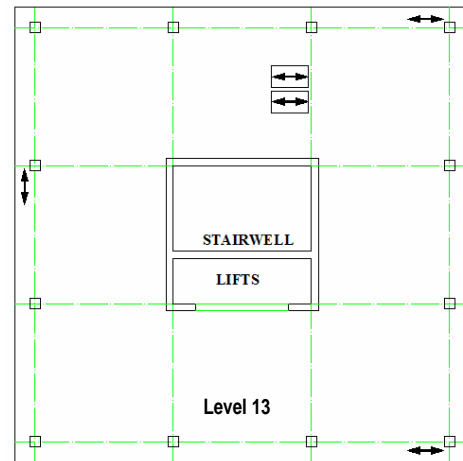


Figure 8 Position of shakers and accelerometers for Test No. 4

2.3 Test No.3

Test No. 3 forced the structure in a diagonal direction by putting the two shakers at 45 degrees within the core of the structure (Fig. 7). The forcing frequencies were same as of Test No. 1. The main idea was to excite both the translational modes in the North-South and East-West directions simultaneously.

2.4 Test No.4

In Test No. 4, shakers were placed away from the centre of the structure outside the core to force the structure to produce predominantly torsional responses. The forcing frequencies were ranging from 2.20 Hz to 2.55 Hz with a step of 0.025 Hz. The setup of the accelerometers and shakers is shown in Figure 8.

3 FINITE ELEMENT MODELLING (FEM)

An elastic three dimensional analytical model was used primarily to compare natural frequencies and mode shapes of the building with that of experimental results. The details and initial Structural

Analysis Program (SAP) model of the building were taken from an earlier study (Lee 2003). The floor slabs were modelled as shell elements. All piles in the foundations had enlarged base diameters and were considered to act as end bearing piles with a high vertical stiffness. The spring supports were used to account for the soil structure interaction effects and the structure also had shear walls in the lower three storeys. The SAP model is shown in Figure 9 and the first three plan mode shapes are shown in Figure 10.

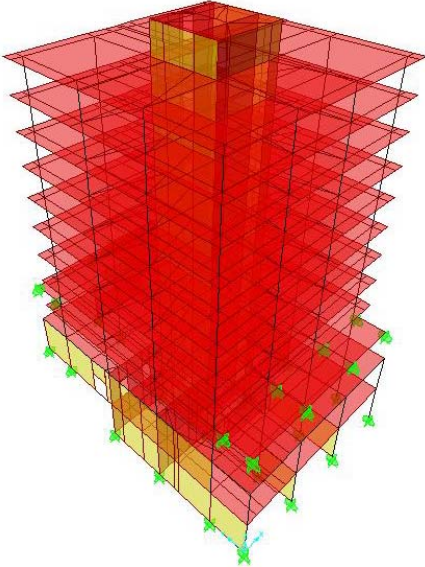


Figure 9 Three dimensional model of the structure on SAP2000

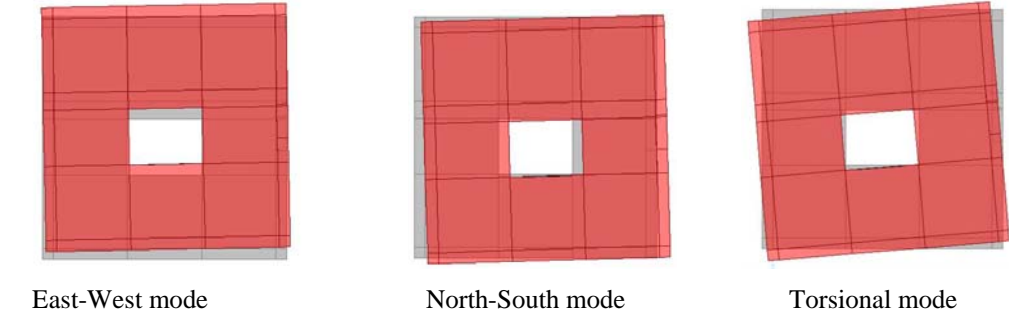


Figure 10 First three plan mode shapes of the structure through SAP2000

4 DISCUSSION OF EXPERIMENTAL RESULTS AND COMPARISON WITH FEM

The objective of these tests was to determine the system frequencies in particular directions. The force amplitude was kept constant during a particular test. The Fast Fourier Transform (FFT) of forced vibration results obtained from Test No.1 is performed for the top two floors and is shown in Figure 11. There is a peak at a frequency of 1.88 Hz in the accelerometers pointing in the North-South direction indicating the first translational mode in this direction. The same treatment was given to the data from Test No. 2 and the Fourier transform is shown in Figures 13. A peak in the data has been observed at 1.76 Hz identifying the first translational mode in East-West direction. Results from Test No. 3 are presented in Figure 15 showing that both the translational modes in the North-South and East-West direction were obtained successfully in a single test. Results from Test No. 4 are shown in Figure 16 indicating the first torsional mode at 2.45 Hz. A problem that was noted in all the tests was that the signal-to-noise ratios were low due to low forcing amplitudes.

A trial and error approach was used to match the frequencies from the initial SAP model and experimental values. It was found that a considerable change in the mass has occurred due to a new green roof on the 13th floor of the structure. The additional mass due to the green roof was calculated

and applied to the initial SAP model. Another attempt was made to change the mass on each floor within a specified range of 5 % in the top floors so as to converge the model frequencies to the experimental frequencies. The results showing the natural frequencies of both the models due to this preliminary updating along with a comparison to experimental results are given in Table 1. There is a need to look into the other uncertain parameters such as stiffness of members, young's modulus of concrete, support conditions etc. to have a better correlation of SAP model with the experimental results.

Table 1. Comparison of experimental and analytical modal frequencies

Sr. No.	Description	Frequencies (Hz)		
		1st E-W mode	1st N-S mode	1st torsional mode
1	Initial model	1.993	2.099	2.385
2	Mass change on 13 th floor	1.943	2.033	2.303
3	Mass change on 6-12th floor	1.782	1.916	2.210
4	Experimental results	1.760	1.880	2.450

The mode shapes has also been obtained for the top eight stories from Test No. 1 and Test No. 2 for first E-W and N-S mode only and normalized results are shown in Figures 12 & 14 along with comparison with the analytical results from SAP 2000 model. The mode shapes for higher modes will be investigated in the forthcoming tests.

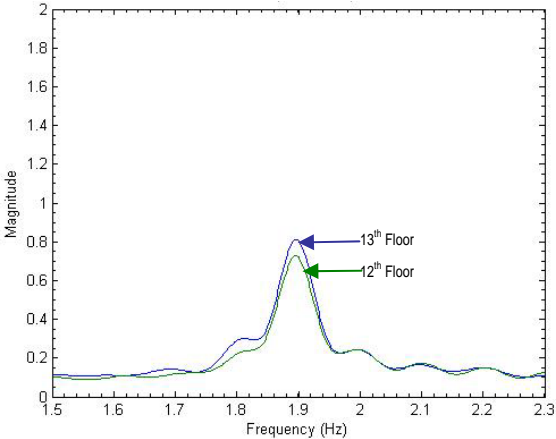


Figure 11 Absolute values of FFT for accelerations in N-S direction for Test No. 1

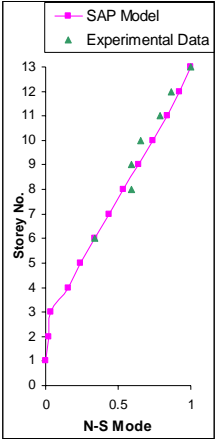


Figure 12 Comparison of experimental and SAP mode shapes for 1st N-S mode

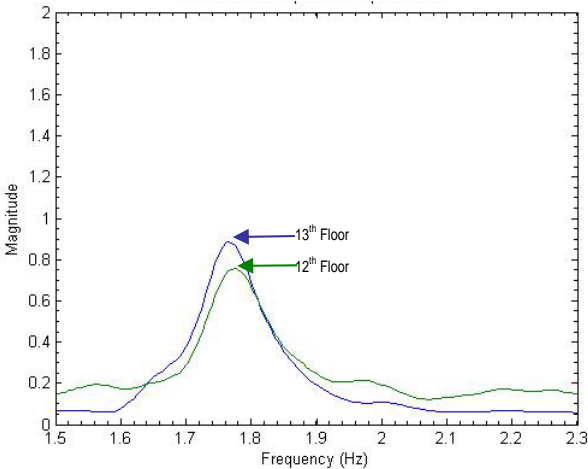


Figure 13 Absolute values of FFT for accelerations in E-W direction for Test No. 2

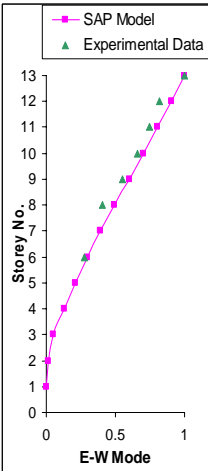


Figure 14 Comparison of experimental and SAP mode shapes for 1st E-W mode

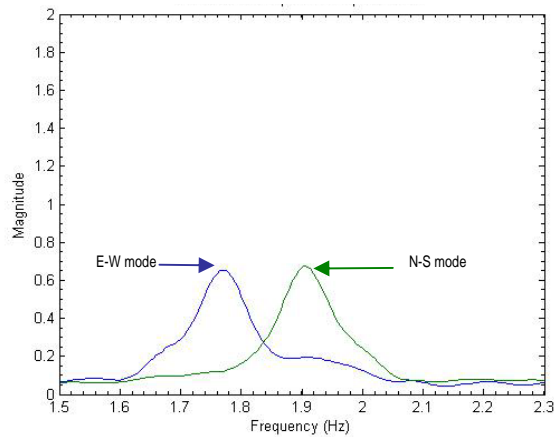


Figure 15 Absolute values of FFT for accelerations in E-W & N-S direction for 13th floor for Test No. 3

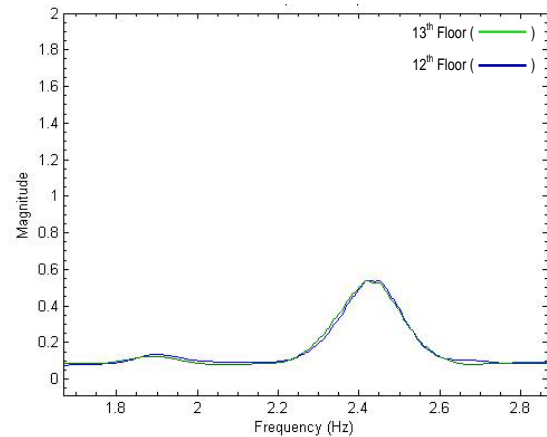


Figure 16 Absolute values of FFT for accelerations for 1st torsional mode for Test No.4

5 CONCLUSIONS AND RECOMMENDATIONS

This paper describes preliminary results of full scale dynamic testing of a 13 storey reinforced concrete building. The main aim of the tests was to have a preliminary insight into the building's dynamic response using small exciters. The first three modes of the structure were distinctly identified with these tests. The first translational mode in the East-West direction was found at 1.76 Hz, first translational mode in the North-South direction is found to exist on 1.88 Hz, and the first torsional mode of the building exists at 2.45 Hz. An FEM model of the structure was formulated using SAP2000 and its predictions were compared to experimental results. A simple model calibration was attempted that yielded a better match between experimental and analytical frequencies. A more detailed and systematic model updating exercise will be done by taking other parameters like stiffness into account. The main advantage of the preliminary tests on the structure is that the test protocols and the target frequencies can now be correctly estimated for the forthcoming tests. Furthermore, these tests have also helped to find the appropriate positioning of the shakers so as to excite all the modes of interest. These tests have proved that a small force can also be used effectively to get the global modes of vibration of the structure and this information can be used to update the analytical model of the structure. Further testing is planned using the recently acquired two ANCO MK-140-10-50 eccentric mass shakers. These can provide a maximum joint force of 200kN and will help to avoid problems with low signal to noise ratio encountered in the present tests.

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