Measurement of Dynamic Characteristics of a Tall Building during Construction

Alan Moore and Graeme Wood
Wind Engineering Services, Department of Civil Engineering, The University of Sydney

June 28, 2004

Abstract: *The dynamic characteristics of a tall-building are determined from full-scale acceleration traces collected at various stages of the construction cycle. The change in the buildings natural frequencies over the construction life cycle are investigated to determine if the natural frequencies of the partially completed structure provides insight into the natural frequencies of the completed structure. Spectral techniques are used to extract natural frequencies from acceleration data, with additional processing using wavelet analysis in circumstances were separate modes of vibration are in close proximity. Natural frequencies decreased as the tower height increased, and it was found that the lower level floor slabs significantly influenced the natural frequencies.*

1 Introduction

Tall structures must be designed so that their wind induced motion does not cause discomfort to occupants. Building designs are becoming taller and more slender, and developers are aiming to achieve more economical designs and construction methods. These factors are leading to buildings that are more susceptible to dynamic excitation by wind. In practice this could lead to a structure that does not meet serviceability requirements for occupant comfort.

Natural frequencies and damping ratios are the parameters that define the dynamic response of structures, and have a significant impact on the design. However, uncertainty surrounds the accurate prediction of these parameters. Natural frequencies and damping ratios of a structure can be measured using full-scale testing techniques once construction is completed, but undesirable results could lead to extremely difficult and costly alterations to the structure if discovered after completion.

The aim of this research is to analyse a numerical model of a tall-building to improve its estimate of natural frequency. Analysis is undertaken by comparing the natural frequencies from a numerical model with those attained from periodic full-scale testing of the partially completed structure. By modelling the structure in a partially completed state, it may be possible to assess the validity of the numerical model and make appropriate adjustments to improve its final preditions.

This paper discusses the results of periodic full-scale testing during the construction of a tall building. Natural frequencies for the fundamental translation modes of vibration are determined via full-scale testing, and significant structural changes resulting from construction are record. By analysing the progressive change in natural frequencies, it is possible that undesirable characteristics can be discovered and acted upon before a structure is completed.

2 Test Structure Details

The structure investigated is a 46 storey office tower, with a maximum height of approximately 190 m above street level. The tower includes 20 m of underground levels, and the base is surrounded by a six storey podium. The floor plan is approximately rectangular, with small rectangular sections of the floor plan removed in the north-east and south-west corners of the tower. The major axes of the building correspond to the cardinal points, and are displayed in Figure 1.

The tower is a composite structure, consisting of reinforced concrete and structural steel components. Core construction is reinforced concrete, with steel beams and a composite slab spanning to the perimeter columns, which consist of concrete filled steel hollow sections. Block work in-fill is used at the core, but is not prevalent in the towers design.

Construction of the tower utilises an existing partially completed reinforced concrete structure, with the core completed to level 23 and floors to level 14. As the tower construction progressed upwards, a substantial amount of demolition work to remove floor slabs and core sections was completed simultaneously. The demolished floor slabs and core sections were re-constructed according to revised designs and alignments.

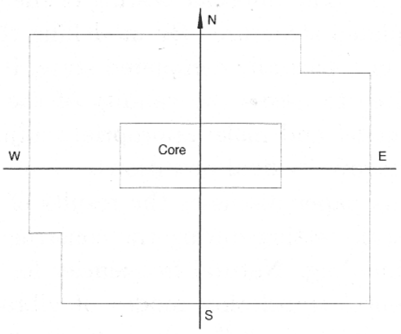

Figure 1: Plan view of tested building with major axes and orientation.

3 Testing Procedure

A pair of orthogonally aligned accelerometers were used to measure accelerations of the partially completed tower. Each accelerometer output was passed to a dedicated signal conditioner to filter and amplify the signal, before being converted to a digital signal and recorded on a computer. The accelerometers were positioned on the highest accessible level of the tower.

The accelerometers captured random vibration from wind loading, and testing was usually conducted in the afternoon as wind velocity is typically higher. Considerable effort was taken to avoid testing while construction work occurred, particularly the operation of the three cranes attached to the tower. However, most of the recorded time series include accelerations generated by the operation of the cranes. Random vibration data and structural progress reports were collected on 18 separate occasions during construction.

4 Data Analysis and Results

Initially, natural frequencies were extracted from the data using a Fourier transform. However, on a number of occasions the natural frequencies of different vibration modes were in close proximity. Most of these cases occurred during the period of construction when the floor slabs between levels 11 and 16 were being demolished and rebuilt, making the tower more susceptible to torsion. In these circumstances, digital filtering was unable to clearly separate the sway and torsion modes.

Previous research [3] has shown the ability of wavelet transforms to decouple multi-component signals. For this research the continuous wavelet transform, Equation 1, and the Morlet wavelet, Equation 2, were used as the transform function and mother wavelet respectively.

$$W(a,t) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(\tau) g^*(\frac{\tau - t}{a}) dt \qquad (1)$$

$$g(t) = e^{\frac{-|t|^2}{2}} e^{j2\pi f_o t} \qquad (2)$$

The wavelet coefficients, $W(a,t)$, are a measure of the similitude between a scaled and translated version of the mother wavelet, $g(t)$, to the signal, $x(t)$, at every instance in time. The Morlet wavelet central frequency (f_o) and scale (a) are directly related to the Fourier frequency f via $f = f_o/a$. The time and frequency resolution of a mother wavelet, and hence its ability to separate closely spaced modes, is governed by its central frequency. To ensure separation of closely spaced modes, a central frequency of $f_o = 3Hz$ was used.

Wavelet anaylsis and its application in Civil Engineering is discussed in more detail in [2].

Figure 2 displays the natural frequencies obtained from the full-scale data as construction of the tower progressed. Both the N-S and E-W first mode natural frequencies are plotted, and an empirical estimate for natural frequency ($f = 46/H$) is included for comparison.

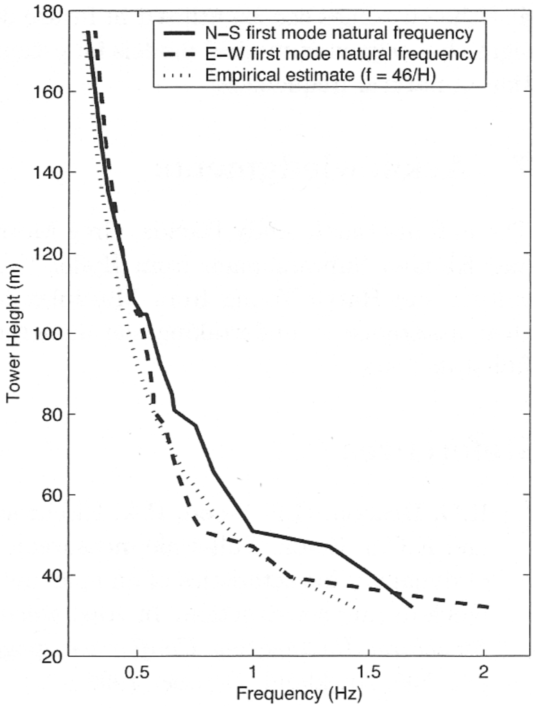

Figure 2: Change in natural frequency during construction.

A number of discontinuities in the lower half of Figure 2 are present. These discontinuities are due to the demolition and reconstruction of the floor slabs between levels 11 and 16 inclusive. As mentioned earlier, construction of the upper levels was not postponed during the re-alignment of the lower floor slabs.

The rapid decrease in natural frequency in the lower portion of the graph corresponds to the removal of floor slabs at levels 13 and 14. After the removal of these slabs, temporary bracing was added to the eastern side of the the structure at level 13. As displayed in Figure 2 the temporary bracing reduced the rate at which the natural frequency decreased.

At a tower height of 105 m, Figure 2 shows a sudden decrease in natural frequencies for no apparent increase in tower height. This sudden change is greater for the N-S fundamental translation frequency compared to the E-W. The frequencies for these points were recorded on the 17 and 24 November 2003, and no change in the height of the structure occurred between those dates. However, the pouring of the previously demolished level 16 floor slab occurred between these dates. Addition of the level 16 floor slab increases the mass of the structure and as a result should reduce its frequency of vibration, although the large magnitude of the change in the N-S direction suggests other factors are also driving the change.

Once the tower reached a height of 105 m, all work on re-building the lower levels had finished. Above this height the N-S and E-W frequencies followed the trend of the empirical estimate, with the N-S frequency converging closer to the empirical estimate as the tower height increased.

5 Discussion

The results indicate that the natural frequencies of the tower decrease with increasing height. Considering the structural system of the tower, the measured natural frequencies correlate well with the empirical estimate, $f = 46/H$. The final 70 m of construction reduced the natural frequency in the N-S direction by approximately 50%, which is a useful result that could be used to verify other buildings of similar structural system at corresponding stages of construction.

Focus was given to accurately recording the structural changes occurring between tests. Even though all significant structural changes where recorded, it is difficult to gauge the influence of all changes on the natural frequencies. However, it can be seen that the lower levels have a significant influence on the natural frequencies. Removing two of the lower levels reduced the natural frequencies by approximately 40%.

Two cranes remained in use during the last testing of the tower. The future removal of these cranes is expected to have no significant effects on the natural frequencies of the tower

— an expectation supported by similar tests conducted on a 94 m high residential tower [1]. This implies that for the purpose of determining natural frequencies, the presence of an unladen crane can be ignored if measurements are recorded at the completion of construction, but prior to removal of cranes. In addition, comparison between random vibration data resulting from wind loading and vibration data from crane loading showed no differences in the natural frequencies detected, which indicates that for the purposes of this full-scale testing, the use of data sets containing crane loading was suitable for determining fundamental translation frequencies.

	N-S (Hz)	E-W (Hz)
Full Scale	0.28	0.31
Numerical Model	0.17	0.19
$f = 46/H$	0.26	-

Table 1: Comparison of fundamental translation frequencies for the completed tower.

The unusual construction of the tested tower provides a number of reference points at which to analyse the numerical model, particularly during the early stages when removal of low level floor slabs had a large impact on natural frequencies. Table 1 compares natural frequencies of the completed structure obtained from full-scale testing with those from the numerical model used in its design. As shown, the difference between these natural frequencies is significant, which warrants a detailed analysis of the model to determine why it incorrectly predicted the natural frequencies.

6 Conclusions

Periodic full-scale testing of a 190 m tall office tower was conducted in order to determine the change in natural frequency as construction progressed. Natural frequencies were extracted from random vibration data, and were found to decrease as the height of the building increased.

The removal of lower level floor slabs had a significant impact on the natural frequencies recorded. From a tower height of approximately 105 m, the recorded natural frequencies compared favourably with those frequencies predicted by the empirical estimate $f = 46/H$.

The N-S fundamental translation frequency predicted by a numerical model of the tower was approximately 40% lower than the value measured from full-scale testing. This discrepancy warrants a detailed analysis of the numerical model in order to improve its predictions, and the outcomes can be utilised in future designs that rely on numerical models for estimation of natural frequencies.

7 Acknowledgments

The authors thank Andy Davids, Greg Morris and Kabilan Subramaniam from Hyder Consulting and Harry Young from Multiplex for their assistance in undertaking the numerous full-scale tests.

References

[1] R.O. Denoon, G.S. Wood, P.A. Hitchcock, and K.C.S. Kwok. Full-scale measurement of dynamic characteristics of an apartment block during construction. In *Australasian Structural Engineering Conference*, pages 501–505, Auckland, October 1998.

[2] K. Gurley and A. Kareem. Applications of wavelet transforms in earthquake, wind and ocean engineering. *Engineering Structures*, 21(2):149–167, February 1999.

[3] T. Kijewski and A. Kareem. Wavelet transforms for system identification in civil engineering. *Computer-Aided Civil and Infrastructure Engineering*, 18(5):339–355, September 2003.