Nineteenth Australasian Wind Engineering
Society Workshop, April 4-6, 2018,
Torquay, Victoria

Monitoring of Building Modal Frequencies, Damping and Accelerations During the Construction Phase of a Tall Rectangular Tower

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ABSTRACT

Full-scale measurements during the construction phase of an approximately 250m high rectangular tower (1.75 : 1 planform ratio) have been conducted enabling a monitoring of the variation of building frequencies during this period. The building accelerations during several strong wind events resulting in almost pure cross-wind response have been analysed. The cross-wind sway mode frequency during these events shows a noticeable dependence upon tower displacement resulting in reductions of the order of 5%. Monitoring of the tower is still in progress and will continue through the final construction phase involving installation of liquid tuned mass dampers.

1. Introduction

The process of designing for structural wind effects on buildings usually commences at the architectural design phase and through to the detailed design phase. In many situations where wind effects result in significant building accelerations, additional auxiliary damping via a tuned mass damper is used to limit the building accelerations and displacements. The process of correctly sizing the auxiliary damping requires full scale measurements of the building to be conducted to gain more accurate estimates of the building stiffness, inherent building damping, energy transfer between modes and orientation of principal structural axes. The extrapolation of wind tunnel data to full-scale properties is sometimes mismatched due to the variability of construction methods and materials (e.g. the measured concrete modulus on the building site is often greater than that specified) and as a result there is an opportunity to refine the size and mass of the auxiliary damping to minimise cost and maximise floor space for the client/builder.

The current study involves an approximately 250m high rectangular planform building (dimensions 34m x 20m or 1.75 : 1 planform ratio) located in the Melbourne CBD. The wind tunnel testing indicated auxiliary damping was required to bring the building serviceability acceleration levels down to the ISO 10137 (Residential) criterion, not mandated by any building code, but typically adhered to as world's best practice. With limited space available on the building roof it was agreed by the builder and structural engineers to monitor the building acceleration over the construction period (and beyond) to gain more accurate estimates of the final building frequencies and damping and hence optimise the design of the liquid tuned mass dampers (LTMD) to be installed on the building roof. The building presents a useful case study, as it is of a uniform geometrical shape, the controlling design moments and accelerations arise from almost pure cross-wind response (in this case in the North-South direction) under exposure to one of the strong prevailing wind directions of Melbourne.

2. Data Acquisition of Full-Scale Measurements

Measurements of building accelerations were acquired using a custom designed accelerometer system, consisting of two pairs of uni-axial accelerometers. The accelerometers are a high sensitivity, low noise model (< 2.5μV rms) from Columbia Research Laboratories Inc. used typically in seismic and low level, low frequency motion studies, capable of measurements in the micro-g range, with a total range of ± 0.5 g. One accelerometer pair was positioned within the building core and the other at the extremity of the building, as shown in Figure 1. The accelerometer system was connected to a PC with data acquisition and a wireless remote connection, enabling direct remote control and download capability from an off-site location. The system was left to run continuously, 24 hours a day, except where power interruptions occurred and construction activities interfered with acquisition, in which case the system had to be relocated. The accelerometer pairs were aligned with the structural axes of the building. The linear combination of signals from the core and edge accelerometer pairs enabled the rotational motion of the building to be determined. The system was progressively moved up the building as construction activities caught up to the monitoring level. Monitoring commenced at Level 47 and has progressively moved up to Level 73 at the time of presenting the data.

Table 1. accelerometer labels and orientation with respect to the building structural axes.

accelerometer label	*orientation*	*modal measurement*
284	- y direction	mode 1 (N-S)
285	- x direction	mode 2 (E-W)
287	+ y direction	mode 1 (N-S)
287	- x direction	mode 2 (E-W)

The acquisition of data was taken at 25Hz for all four accelerometers simultaneously. The system exported hourly data files, every hour, on the hour as well as 5 minute, 10 minute and 24 hour summary text files which contained the highest acceleration for each accelerometer over the prescribed time period. These proved useful to track down specific data files during significant wind excitation events.

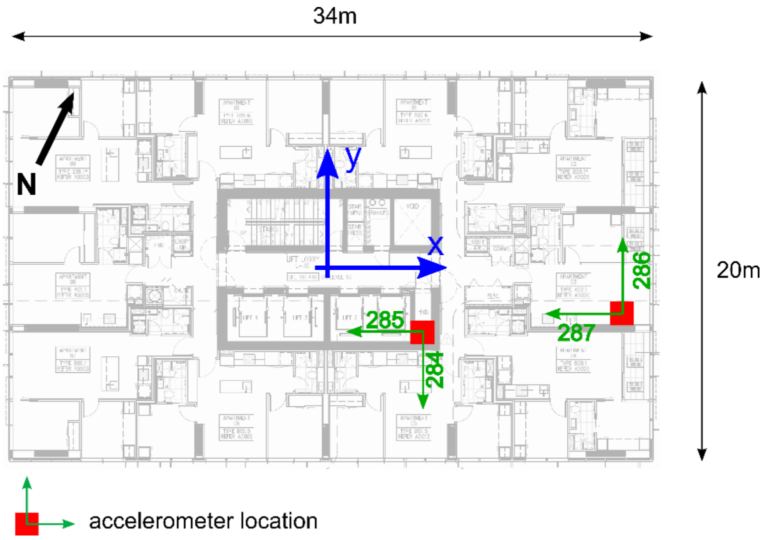

Fig. 1. Building axis coordinate system and accelerometer placement

3. Results

A plot of the variation of building frequency for the first two sway modes (N-S direction mode 1, E-W direction mode 2) over time is presented in Figure 2. The variation of frequency during the building construction is clearly evident. Gaps in the data correspond to periods when the operation of the monitoring system was not possible due to a combination of construction activities and availability of space to relocate the system in a suitable area. The N-S sway mode frequencies can be seen to vary from approximately 0.21Hz, at the commencement of the monitoring, at the end of the first quarter of 2017, down to 0.13Hz when the primary building structure had been completed (top-out stage). The second mode (E-W motion) sway frequencies were observed to follow an almost parallel decline in frequency, relative to the first mode, from approximately 0.25Hz to 0.165Hz. For a period of approximately 2 months after top-out both sway mode building frequencies remained relatively constant, as indicated by the plateau in the measurements. However towards the end of the first quarter of 2018 a further drop was observed in both sway mode frequencies. This was evidently due to the erection of additional secondary structure on the roof of the building, indicating the sensitivity of building frequency on modal mass, particularly when situated at the top of the building

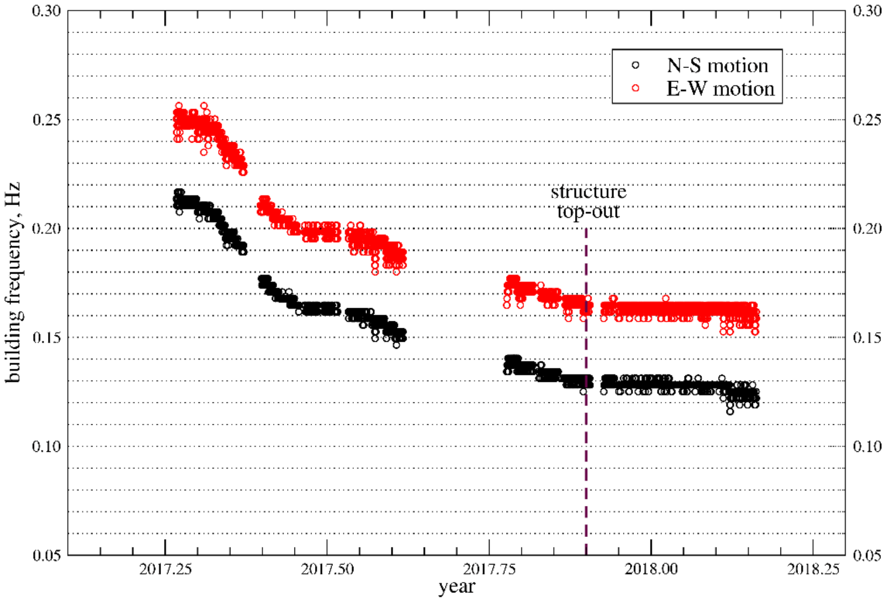

Fig. 2. Variation of building sway mode frequencies with time.

A further feature of the building frequencies presented in Figure 2 is the scatter, or excursion of building frequencies from their nominal values at the same instant in time. For example the date corresponding to 2018.125 (February 14th, 2018) shows a significant variation in measured building frequency over a period of 24 hours. This variation for mode 1 is highlighted in Figure 3a. The measured frequency is observed to drop from 0.128Hz at 00:00hrs of the 14th February to 0.116Hz at 10:00hrs then return back up to approximately 0.125Hz at 24:00hrs; a drop of between 5% - 10% of the nominal building frequency. During this period there was no major construction activity (i.e. crane lifting, or addition of any significant structural or mass elements) due to the high winds. Superimposed on this plot is the standard deviation of building acceleration in the y-direction. A strong wind event was incident upon the building at about 09:00hrs, which was measured to be approximately 120km/h at the top of the building, measured with a local wind anemometer. The wind was incident from the west, which induced an almost pure cross-wind motion (y direction or N-S motion) on the tower. It is therefore clearly evident from the data that there is a relationship between building frequency and acceleration (or equivalently displacement).

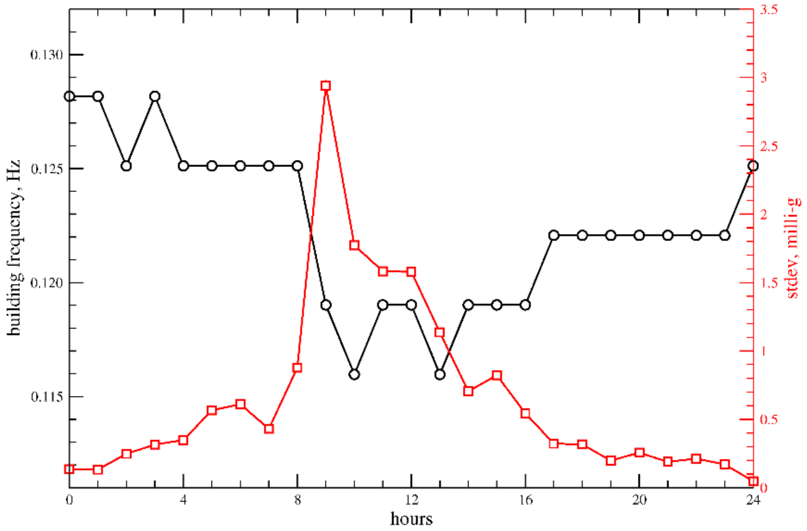

Fig. 3. Variation of mode 1 building sway mode frequency over a period of 24hours during 14th February, 2018.

The time history of the y direction acceleration over the hour period from 08:00hrs to 09:00 hours is presented in Figure 4. The strong wind event can be seen to arrive about 40minutes into the hour. The y-direction accelerations show excursions above 10milli-g, during which the motion was noted as being sensed by the construction workers working within the tower at the time of the event. Note also, that the response is predominantly cross-wind, as the x-direction (E-W) accelerations show only a small increase in amplitude during the wind event, and the corresponding ellipse plot of the x-y accelerations, shown in Figure 4, displays a relatively narrow profile, oriented almost directly in line with the y-direction.

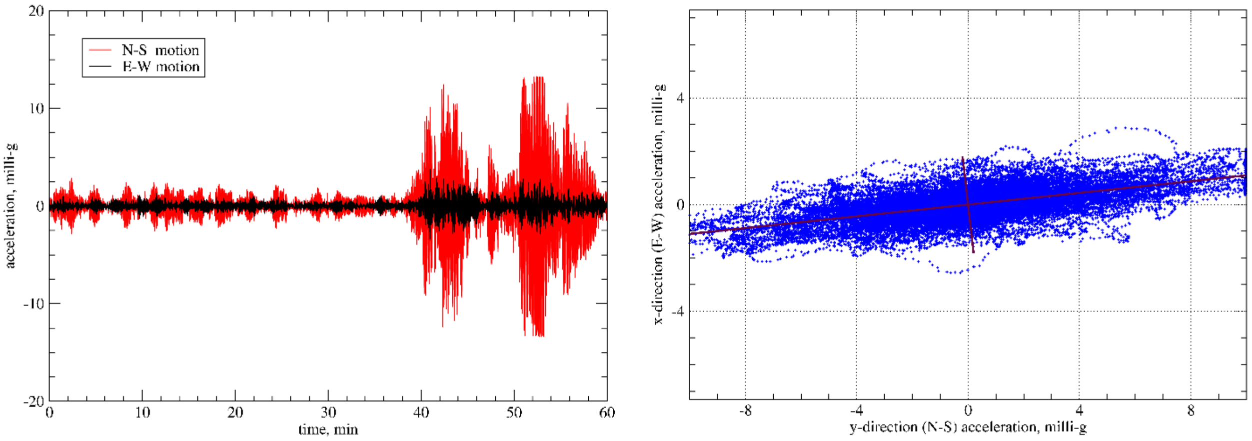

Fig 4. Time history of y-direction acceleration at Level 73 from 08:00hrs to 09:00hrs on 14th February, 2018, and corresponding x-y acceleration ellipse plot.

Such a dependence of building frequencies with amplitude of oscillation has been documented by Udwadia and Trifunac (1974), Tamura and Suganuma (1996), Tamura (2012) and Kashima (2017), amongst others. Their data indicates variations in building frequency of approximately 5% as a result of large amplitude oscillations. Tamura (2012) suggests that the variation in building frequency with amplitude may be attributed to the secondary structural members and that the reduction would expect to asymptote beyond a certain amplitude threshold . The present data shows a reduction in the first mode frequency, under almost pure cross-wind excitation, of between 5% and 10% relative to the frequency for low amplitude acceleration levels, i.e. $\sigma(\ddot{y})$ < 0.5 milli-g. The research literature also presents evidence of building damping varying with amplitude of oscillation or equivalently building tip acceleration. In the present case the full-scale data is still being analysed and extraction of the building damping characteristics is currently work-in-progress.

4. Conclusions

The results of the full scale monitoring to date have shown a strong dependence of building frequency with amplitude of building accelerations. The building damping characteristics are currently being analysed and will be presented at the Workshop. Furthermore, with building monitoring still in progress, additional data is still being acquired and with damper tank installation imminent in the next few weeks. The effect that these will have on the building motion will continue to be monitored and evaluated over the next 12 months.

Acknowledgements

This work was done in conjunction with Robert Bird Group structural engineers and Probuild Constructions Pty Ltd and their permission to use and release this data for publication is kindly acknowledged.

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