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BRE Client Report

Acceleration Comfort Study of the proposed Vitra Tower at Balneário Camboriú, Brazil

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Executive Summary

It is planned to develop a site in Balneário Camboriú with a proposed scheme known as the Vitra Tower. This development will consist of a residential tower, the total height of which is 224m; the first eight storeys consists of ground and mezzanine floors, 4 floors of garages, and a recreation floor. Above these storey are 53 residential storeys, above which are luxury apartments, a terrace, a plant room and a water tank.

BRE conducted a wind tunnel study to determine the dynamic response of the Vitra Tower. A 1:300th scale model of the site and the surrounding area was tested in a BRE boundary layer wind tunnel. Measurements of the external wind pressures were taken at 201 locations around the surfaces of the model. Using the Brazilian HFPI Approach, the wind tunnel measurements were integrated to obtain time-varying forces and moments, which were then combined with the dynamic structural properties of the Tower.

The worst-case peak acceleration responses at the top occupied floor (Level 64) of the Vitra Tower were calculated for a range of return period wind speeds. The predicted acceleration levels of the Vitra Tower were compared with Melbourne's acceleration comfort criteria. It was found that for all approaching wind directions the expected peak levels are less than Melbourne's threshold levels. Consequently the acceleration motion of the Vitra Tower is not likely to create unacceptable levels of occupancy comfort. Therefore it is unlikely that complaints would be expected from residents living towards the top of the Tower

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1 Introduction

Balneário Camboriú is a rapidly growing commercial centre and seaside resort located on the East Atlantic coastal plain of Brazil. Balneário Camboriú is located next to a beach that faces towards the Atlantic Ocean. The area along the sea-front contains tall isolated towers, whereas the buildings that form the majority of Balneário Camboriú consist of low-rise residential buildings. Beyond the outskirts of Balneário Camboriú are hilly areas that are used for agricultural activities.

It is planned to develop a site in Balneário Camboriú with a proposed scheme known as the Vitra Tower. This development will consist of a residential tower, the total height of which is 224m; the first seven storeys consists of ground and mezzanine floors, 4 floors of garages, and a recreation floor. Above these storeys are 50 residential storeys, above which is a plant room and water tank.

A contract has been agreed with Pasqualotto to test the Vitra Tower in the BRE wind tunnel. Wind tunnel tests were undertaken during February 2017 to determine the accelerations acting on the top occupied floor (Level 64) of the proposed development. The testing was carried out at BRE, Bucknalls Lane, Watford, WD25 9XX, UK. The work was conducted by BRE as project P104250 under the BRE Terms and Conditions for Testing.

This report describes the wind tunnel tests carried out and presents the results obtained.

2 The model and atmospheric boundary layer simulation

A wind tunnel model of the Site was constructed for the purpose of these tests by Model Products Limited. The model featured the buildings of the proposed development and the surrounding buildings. A photograph of the model mounted in the wind tunnel is shown as Figure 1; the area of woodland to the West of the site can be seen in the foreground.

The linear scale of the wind tunnel model was 1:300 and it was constructed on a circular baseboard of diameter 1.75m. The surrounding area was therefore represented up to a radius of approximately 263m. The wind speed measurement reference height was 750mm above the wind tunnel floor, which corresponds with a full-scale height of 225m above the ground.

The areas surrounding the site consist of city centre buildings; wind blowing from the suburbs beyond the immediate surroundings corresponds with Terrain Category IV of the Brazilian wind loading Code of Practice, NBR 6123 (Ref[1]). For each approaching wind direction the appropriate atmospheric boundary layer was simulated at the appropriate scale using rectangular plate roughness elements. The rectangular elements create a mean velocity profile, turbulence profile and turbulence spectra appropriate to the area surrounding the Site.

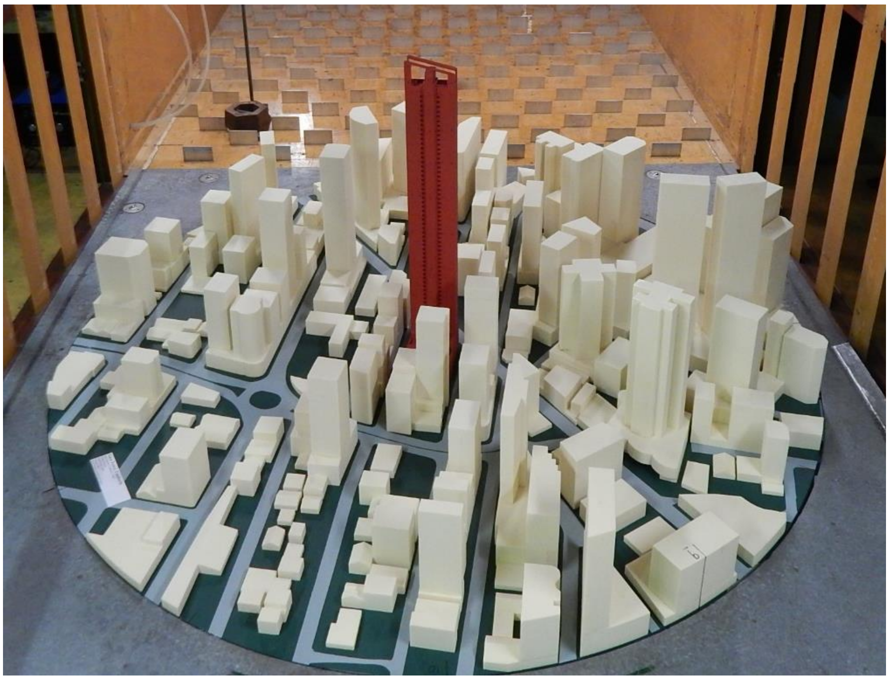

Figure 1: The Vitra Tower model in the BRE wind tunnel (looking towards North)

Pressure tappings were inserted at locations around the model surface. The tapping positions were chosen to give a good coverage of the Vitra Tower, as well as being placed at locations likely to experience high local suctions. The locations of the taps are shown in Appendix A. The pressure taps were mounted flush with the model surface, and connected via standard lengths of tubing and restrictors to pressure transducers mounted beneath the model.

A total of 201 pressure measurement points (tap locations) were used in this study. The pressure tap numbers used in this study are 2 – 202. Note that Tap 1 is used to measure the wind tunnel reference conditions, and is therefore not present on the model.

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3 Method of testing and analysis

Atmospheric wind simulation

The areas surrounding the Site consist of city centre buildings, beyond which are suburban buildings. For each approaching wind direction the appropriate atmospheric boundary layer was simulated at a linear scale of 1:300 using rectangular plate roughness elements. The rectangular elements create a mean velocity profile, turbulence profile and turbulence spectra appropriate to the area surrounding the Site.

The mean velocity of the wind tunnel was measured by a pitot-static tube mounted at a point 750mm above the wind tunnel floor. Since the linear scale of the model is 1:300, this pitot-static tube location corresponds to a full scale height above the ground of 225m. The pitot-static tube was used to measure the reference mean wind and was recorded for each wind direction.

Wind pressures were measured using miniature electronic ZOC (Zero, Operate, and Calibrate) pressure scanners manufactured by Scanivalve Corp. These sensors are piezo-resistive differential sensors with a sampling rate of up to 20kHz and a full scale pressure range of 10 inch of water (1250Pa). Models ZOC22B, ZOC 33 and ZOC 64 modules were used for this study. All modules are extremely compact, multi-pressure scanners with either 32 or 64 individual silicon pressure sensors. All modules include a high speed multiplexer (20kHz), and an instrumentation amplifier. These units are specifically designed for use in wind tunnel testing.

Provided the wind is fully turbulent (which occurs at wind tunnel speeds above about 1m/s), the wind tunnel can be run at any nominal speed setting. Appropriate scaling factors and non-dimensionalised processes are applied during the data acquisition and subsequent analysis. This method means that the correct full scale wind pressures are ultimately derived from the measured data.

Calculation of Wind Tunnel Scaling Factors

The “basic” windspeed, V_0 is the 3-second gust speed 10m above open level countryside, having a return period of 50 years. Navegantes Airport is near to the Atlantic coastline, about 10km North of Belneário Camboriú. WSYS are a Brazilian company that provides and analyses meteorological information, including wind data. Wind records from an anemometer 10m above the ground at at Navegantes Airport were analysed by WSYS to find the predicted 50 year return period gust speed; details of this analysis are given in Ref[2].

The WSYS data provided in Ref[2] was obtained from measurements taken from the airport anemometer; near to this anemometer are low-rise buildings. No corrections were made by WSYS to correct the data to open level, countryside conditions, which is a requirement of V_0. As explained in Ref[3], a 10% increase of the WSYS gust speed data was required to correct the WSYS data to V_0.

The maximum 3-second gust speed provided by WSYS in Tabela 2 of Ref[2] is 31.7m/s. Hence the value of V_0 used in this study was 1.1x31.7 = 34.9m/s.

To convert a basic windspeed value to the equivalent mean windspeed, $V_{10,r}$ the following equation (given in Ref [4]) was used:

$$\frac{V_0}{V_{10,r}} = 1 + \frac{\beta^{1/2}c(t)}{2.5ln\left(\frac{10}{z_0}\right)} \quad \ldots(1)$$

For open level ground the surface roughness parameter z_0 = 0.03, and β = 6.32. For a 3 second gust, $c(3)$ = 2.68. Noting that V_0 = 34.9m/s, substituting the above values into Equation (1) gives $V_{10,r}$ = 21.7m/s. This windspeed relates to open level ground conditions, which is the same terrain condition at which the basic windspeed conditions were measured.

A correction needs to be applied to account for the differences in height between 10m (the basic windspeed measurement height) and the 225m full-scale wind tunnel reference windspeed height; this correction is the S_2 factor given in NBR 6123 (Ref[1]). The S_2 factor depends upon building size, height above the ground and the Terrain Category; values of S_2 are given in Tabela 2 of NBR 6123. In this study the effects upon the cladding are being considered. Therefore the Class A values given in Tabela 2 were used (Section 5.3.2 of NBR 6123). At a height of 225m above the ground, for winds blowing over open countryside (Terrain Category II), S_2 =1.30. Hence the mean design windspeed 225m above the ground at Camboriu is 21.7x1.30 = 28.2m/s.

As noted earlier, when the simulated wind is fully turbulent the wind tunnel can be run at any nominal speed setting. Appropriate scaling factors and non-dimensionalised processes are applied during the data acquisition and subsequent analysis. This method means that the correct full scale gust pressures are ultimately recovered from the measured data. For this investigation, the wind tunnel was run at a nominal model scale speed of 10.0 m/s (as measured by the pitot-static tube), which corresponds with a velocity scaling factor of 28.2/10.0 = 2.82.

The velocity scaling factor and the linear scale of the model (1:300) fixes automatically the wind tunnel time scale at 106 (300/2.82), and the pressure scaling factor at 7.95 (2.82^2).

Measurements were made for 36 wind directions in 10° increments. All of the wind directions (or azimuth angles) are quoted in degrees east of North. For example, winds coming from the West have a corresponding azimuth angle of 270º.

Form of the analysis

Measurements were made for 36 wind directions in 10° increments. All of the wind directions (or azimuth angles) are quoted in degrees east of North. For example, winds coming from the West have a corresponding azimuth angle of 270º

Positive forces in the x and y directions, and the positive twisting moment direction are shown on Figure 2; these directions correspond with the positive x, y and rotational axes directions. Negative forces and directions act in the opposite directions to these positive axes directions.

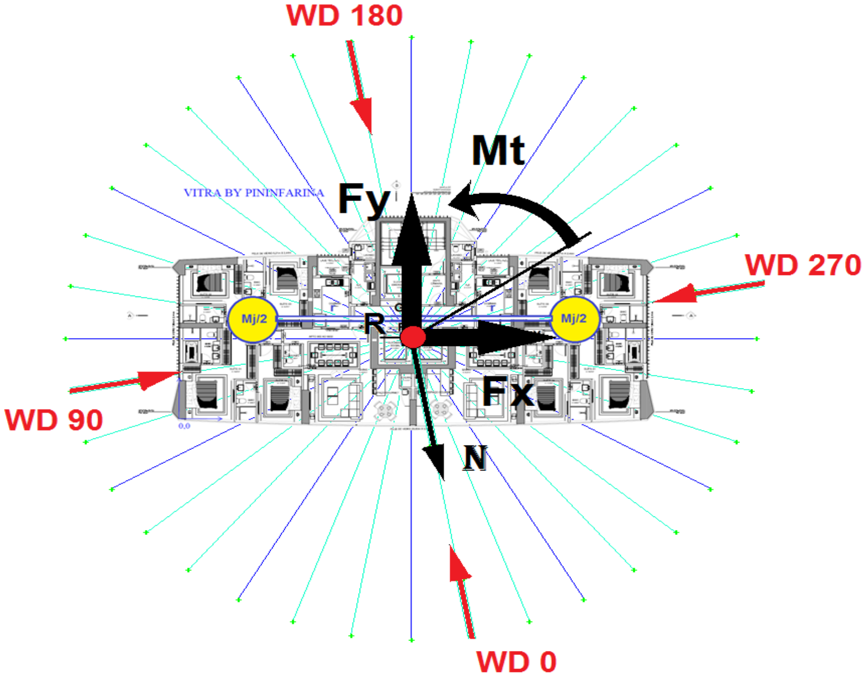

Figure 2. Plan of Vitra Tower Showing Co-ordinate System Axes

Wind pressures were measured in the wind tunnel at each of the pressure tap locations. The sampling rate of these pressures was ¼- second in full scale; the sample length of the measurements was equivalent to 8.5 minutes in full scale time. Using the wind speeds described earlier, the equivalent pressures with an annual probability of occurrence of 0.02 (a return period of 50 years) were calculated.

To obtain the accelerations acting on the Vitra Tower, the simultaneous measured pressures around the tower were integrated using appropriate area weights. This process was undertaken for both the x- and y-axis directions shown on Figure 2, as well for the twisting moments about the vertical (z-) tower axis. The direction of North is also indicated on Figure 2. This means that a positive x-direction force acts Westwards, a positive y-direction force acts Northwards, and a positive twisting moment acts anti-clockwise.

At each of the rings of taps A-K shown in Appendix A the peak quasi-static forces and moments were calculated. For a given tap ring the forces and moments were obtained by integrating the measured surface pressures up to and including that tap ring. The quasi-static peak wind-induced forces and moments at each floor were obtained by linear interpolation between the loads attributed to each tap row.

The dynamic response of the Vitra Tower was calculated using the Brazilian High Frequency Pressure Integration (HFPI) approach. As described in more detail below, this method combines the wind-induced forces and moments (obtained from the wind tunnel tests) with a structural model of the Vitra Tower. This combination enables the time-varying dynamic motion of the Tower to be predicted. From this motion, the accelerations of the top occupied floor of the Tower can be determined. The accelerations of this floor were calculated for a range of Return Period wind speeds, which enables the acceleration behaviour to be compared with established acceleration comfort criteria.

For this study a structural damping ratio of 1.5% was used. For concrete buildings with shear walls, a damping value of 1.5% is specified in the Brazilian wind loading Code of Practice NBR 6123 (Ref[1]).

Effect of Return Period

Strouhal Number Similarity

The wind tunnel testing was conducted to simulate the 50 year return period wind speed conditions. That is, the wind tunnel velocity scale, the model linear scale and the time scale were matched to full-scale conditions that correspond with the 3-second basic windspeed, V_0 (34.9m/s). These three scales are noted below.

As described above the wind tunnel was run at a speed of 10m/s, and the mean speed of the reference height was 28.2m/s (which corresponds with a V_0 of 34.9m/s). Therefore,

Velocity scale (velocity full-scale/velocity model) = 28.2/10 = 2.82.

Linear scale (length full-scale/length model) = 300/1 = 300.

Time scale (time full-scale/time model) = 300/2.82 = 106

Matching these three scales correctly means that the Strouhal number
([length scale /time scale]/velocity scale) must equal unity, viz: (300/106)/2.82 = 1.00.

As an aside, in the literature the Strouhal number S_t is more usually related to the frequency n, the velocity V, and the cross-wind length b, by means of the expression S_t = (bn)/V. Since frequency is the reciprocal of time, it can be seen that this equation and the earlier Strouhal number expression (using the three scales) are equivalent.

With regards to wind tunnel testing, ensuring that the Strouhal number is unity (known as “Strouhal number similarity”) is very important. This is because effects of vortex shedding of the model building being tested, and vortex shedding of wakes from surrounding model buildings are both frequency and windspeed dependent. The Strouhal matching process ensures that these effects are properly taken into account by the wind tunnel testing.

Wind Tunnel Data Collection

As noted earlier, the Strouhal number was matched to data collected at ¼ second full-scale time intervals, and the V_0 (50 year Return Period) windspeed conditions. As shown below, to maintain Strouhal number similarity, lower windspeed conditions can be simulated by either running the wind tunnel more quickly, sampling the data more quickly, or a combination of both techniques. For example, in the wind tunnel testing undertaken in this study, to measure ¼ second full-scale data, the sampling rate of the data collected in wind tunnel is 106x4 = 424 samples per second (Hz). If the required wind speed conditions are 50% of the V_0 wind conditions, and the wind tunnel run at the same speed of 10m/s, the velocity scale is (28.2/2)/10 = 1.41. The linear scale of the model is the same (300), and the time scale is therefore 300/1.41 = 213. Hence a ¼ second sampling rate now corresponds with a data collection rate of 213x4 = 852 Hz.

Bearing in mind that BRE routinely measures more than 300 channels of pressure simultaneously, the equipment we presently use is not able to sample this number of channels at 852 Hz.

An alternative way to simulate the 50% V_0 wind conditions correctly (i.e. the Strouhal scaling number is unity, thus maintaining Strouhal number similarity) is to run the wind tunnel twice as quickly (at 20m/s) and to keep the sampling rate at 424 Hz. Running at such high tunnel speeds would mean that the models mounted in the wind tunnel would have to be made very strong to withstand the wind forces, and the baseboard (onto which the model is mounted) would have to be stiffened. A further practical effect that needs to be considered is the frequency-dependent attenuation and amplification that can occur as the pressures pass from a surface pressure tap - along pressure tubing – to the pressure transducer location.

The methods described above can be used to simulate the effects of different wind speeds. However, there are testing cost implications if the wind tunnel has to be run over a range of different speed settings, and/or the pressure measurements sampled at different rates. As a result, data collected at a Strouhal number of unity has historically been non-dimensionalised to create pressure coefficients, and these coefficients thereafter scaled by means of the required full-scale velocity in order to create the predicted effects. This approach is consistent with Codes of Practice, but it is nevertheless incorrect because it does not maintain the Strouhal number similarity. A new approach to this problem is described below, and the new method has been used to predict the acceleration behaviour described in this report.

High Frequency Pressure Integration (HFPI)

The “Brazilian HFPI Approach” method (Ref [5]) was used to produce the results presented in this study. Essentially, this method combines properly the wind tunnel measurements of the external façade time-varying wind loads (acting on each floor of the building) with the dynamic structural properties of the building. As well as the mass distribution of the building, the dynamic structural behaviour can be modelled a summation of the effects of the “modes of vibration” of the building structure. A mode of vibration is a property of the building structure. Each mode of vibration occurs at a specific frequency (known as “natural frequency”) and has a unique pattern in space or (known as a “mode shape”). The fundamental (or lowest mode of vibration) occurs at the lowest natural frequency of the structure, and the higher mode numbers (e.g. the second mode, third mode, etc.) occur at successive higher natural frequencies.

If the correct modal participation factors are calculated (e.g. using HFPI), at any given building location, the resulting time-varying building motion can be predicted by adding together the products of the mode shapes and the modal participation factors. In theory, the effect of an infinite number of modes is required to describe the motion. In practice, for buildings the modal participation factors reduce quickly as the vibration mode number increases. This means that for buildings and towers such as the Vitra Tower, the effects of the ten lowest mode shapes need only be considered.

As described above, the HFPI approach predicts the time-varying motion of a building. For this study, 2048 time-varying displacements of each floor of the Vitra Tower were taken at a full scale sampling rate of ¼ second; the full-scale length of time of the record length is therefore about 8.5 minutes (2048/[4x60]). The accelerations at the top occupied floor of the Tower were be obtained by differenting these time-varying displacements twice with respect to time.

The Brazilian HFPI method creates modal participation factors which relate specifically to wind tunnel data collected at a full-scale rate of ¼ second (4 Hz). These modal participation factors thereby relate directly to the natural frequencies of the building structure, and it is for this reason that this approach is able to quantify the amount of vibration that occurs in any given vibration mode.

Determining Effects of Windspeed Changes

The effects of windspeed change upon wind-induced forces and accelerations are two-fold. The first well-established effect of windspeed change is that the magnitudes of the forces produced increase/reduce in proportion with the square of windspeed. As described below, the second effect relates to Strouhal number similarity.

As described earlier, the modal participation factors are related to specific (full-scale) frequencies. As shown above, Strouhal number similarity means that an effect of a windspeed change is the necessity to change the wind tunnel timescale. For example, as shown above, halving of the approaching windspeed necessitates a doubling of the sampling rate. This known relationship between windspeed and frequency means that the modal participation factors can, when shifted in the frequency domain, be summed together over all mode shapes, to predict the effect of the building motion (with wind forces and dynamic motions that correspond with a 50 year Return period).

Therefore, i) by shifting the frequency of the modal contributions, and then ii) by scaling the resulting Tower motion by the square of the windspeed ratio, the predicted building motion thereby maintains the Strouhal number similarity; this similarity is essential to be able to identify whether or not vortex shedding effects occur at lower windspeeds.

The frequency shifting approach is limited by the condition that the sample time intervals need to be small enough (or the frequencies high enough) that they enable the accurate computation of the amplification effects. The Nyquist Sampling Theorem states that no frequency information at all can obtained for frequencies that are more than half the sampling rate. This requirement means that this method cannot be used to predict the effects of very low windspeeds. Nevertheless, for the Vitra Tower project, the accuracy of the computation is acceptable within the range of windspeeds which correspond to Return Periods between 5 and 50 years

The above frequency-shifting and velocity-scaling approach has been used to determine the acceleration results presented in this report. These results were obtained for Return Periods between 5 and 50 years.

Results

For the 36 approaching wind directions, the predicted acceleration behaviour of the top occupied floor of the Vitra Tower (Level 64) are shown on Figures 3-6. The predicted acceleration levels are compared with the peak threshold acceleration levels for human comfort suggested by Melbourne (Ref[6]).

The results presented in Figure 3-6 show that for all of the approaching wind directions, the predicted accelerations are lower than Melbourne's comfort criteria threshold. In practical terms, these findings mean that complaints from the residents are unlikely.

For a 10 year return period (which is often used as benchmark in this type of study), the worst-case expected peak acceleration level at the top occupied floor of the Vitra Tower is 0.180 m/s^2, or 18 milli-g. This means that the acceleration level of 18 milli-g has a 1-in-10 probability of being exceeded in any given year. Note that the acceleration levels are predicted to occur at the top occupied floor of the Tower. Locations near to the Tower centre of twist, and locations lower down the lower will have lower predicted acceleration levels.

Many studies have been undertaken to quantifying levels of human perception to acceleration. With regards to wind-induced building vibration, the standard acceleration levels shown in Table 1 (taken from CEB 209 (Ref[7]) are used for indicative purposes at BRE. Hence an 18 milli-g level of vibration of the building could be perceived as being "annoying" by a small percentage of the occupants.

Acceleration level	Human perception of movement
< 5 milli-g	Imperceptible
5 milli-g to 15 milli-g	Perceptible
15 milli-g to 50 milli-g	Annoying
50 milli-g to 150 milli-g	Very annoying
> 150 milli-g	Intolerable

Table 1. Human Perception of Building Vibration Due to Wind

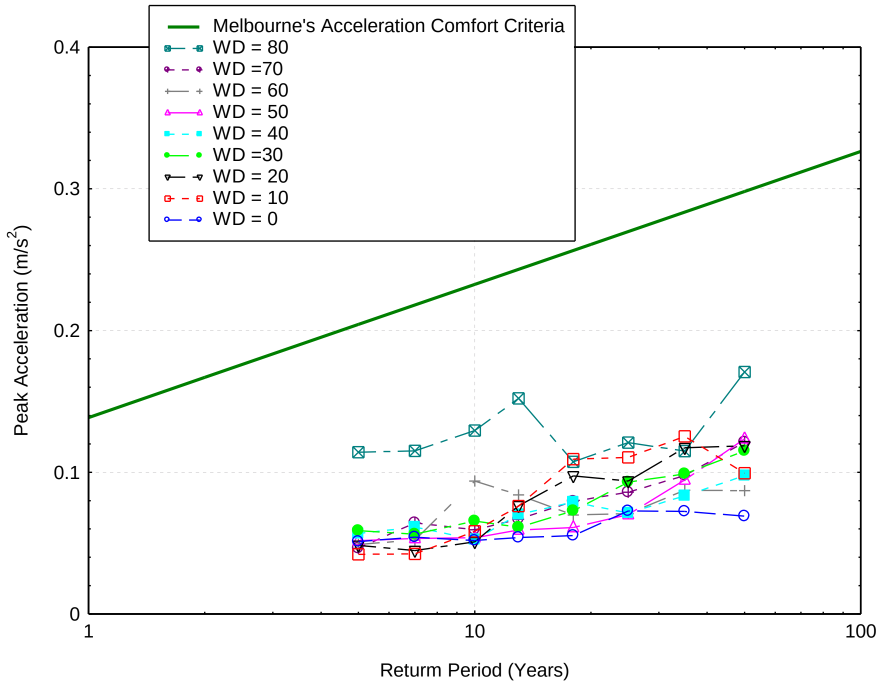

Figure 3. Predicted Acceleration Response of Top Occupied Floor of Vitra Tower (1.5% damping) (Wind Directions 0 - 80)

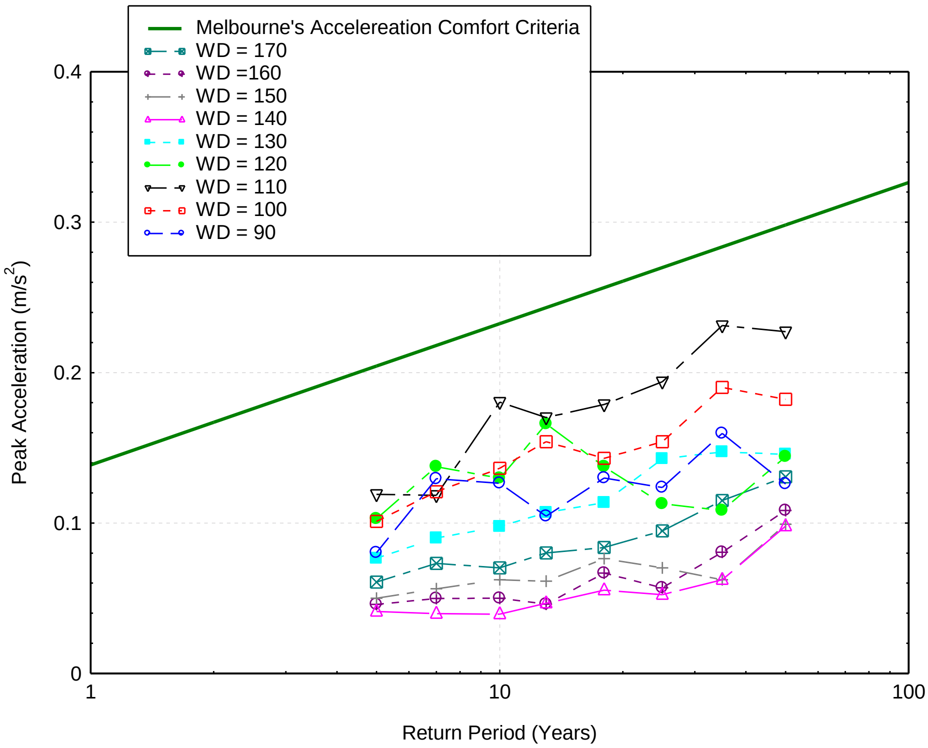

Figure 4. Predicted Acceleration Response of Top Occupied Floor of Vitra Tower (1.5% damping) (Wind Directions 9 - 170)

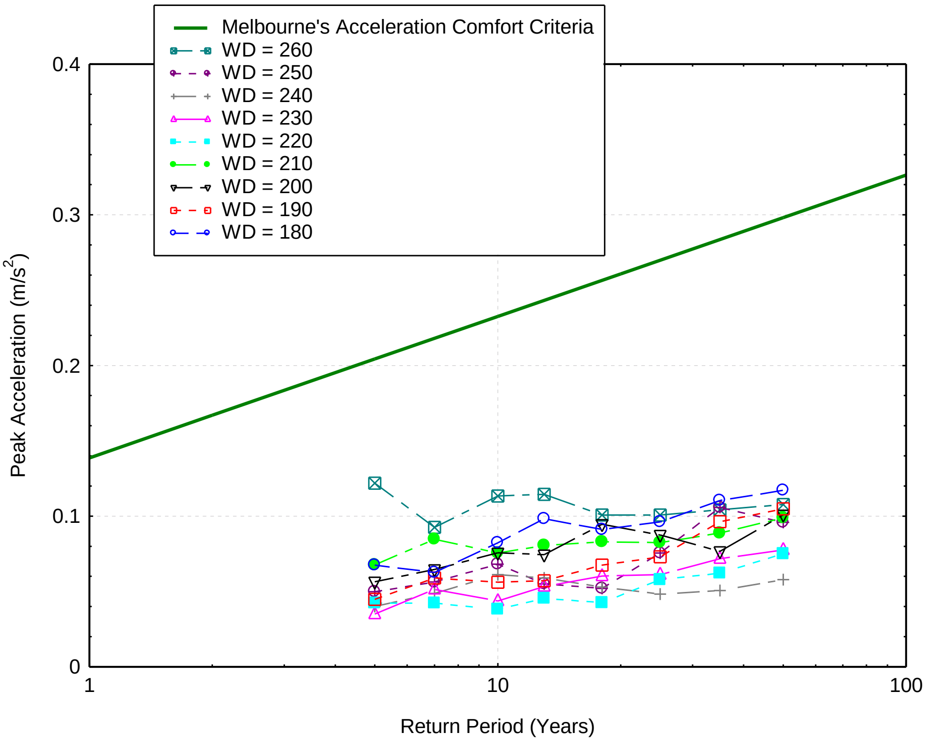

Figure 5. Predicted Acceleration Response of Top Occupied Floor of Vitra Tower (1.5% damping) (Wind Directions 180 - 260)

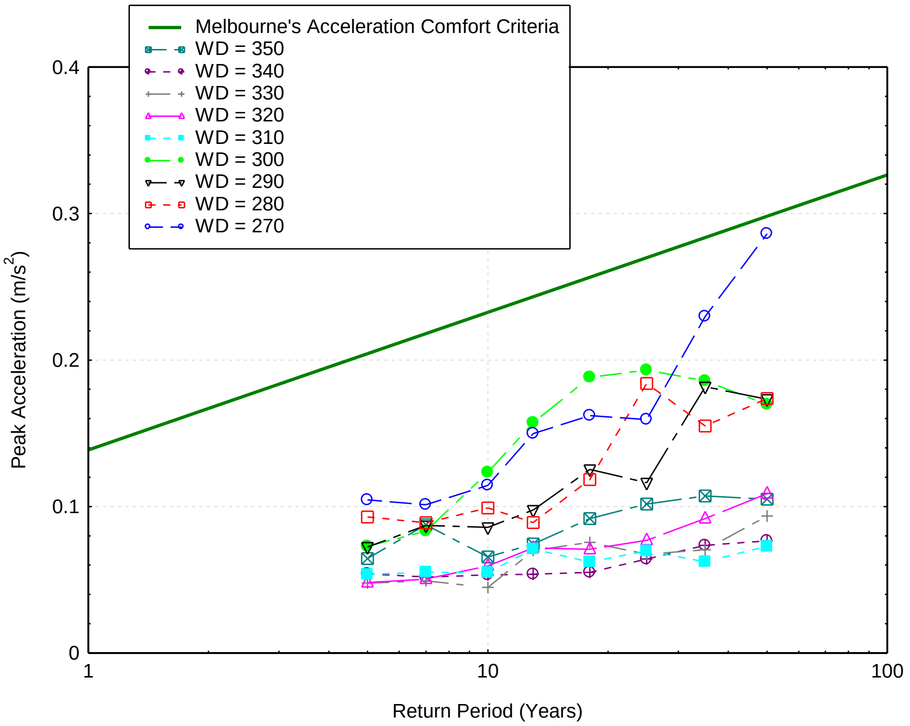

Figure 6. Predicted Acceleration Response of Top Occupied Floor of Vitra Tower (1.5% damping) (Wind Directions 270- 350)

Conclusions

BRE conducted a wind tunnel study to determine the dynamic response of the Vitra Tower in Balneário Camboriú Brazil. The results from this study were combined with structural parameters supplied to BRE to determine the dynamic response of the Tower to the wind-induced forces.

The worst-case peak acceleration responses at the top occupied floor (Level 64) of the Vitra Tower were calculated for a range of return period wind speeds. For a structural damping ratio of 1.5% the results are presented in Figures 3-6. Locations near to the tower centre of twist, and locations lower down the Tower will have lower predicted acceleration levels.

The predicted acceleration levels of the Vitra Tower were compared with Melbourne's acceleration comfort criteria. It was found that for all approaching wind directions the expected peak levels are lower than Melbourne's threshold levels. Consequently the acceleration motion of the Vitra Tower is not likely to create unacceptable levels of occupancy comfort. Therefore it is unlikely that complaints would be expected from residents living towards the top of the Tower

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