Wind Effects on Naturally Ventilated, Enclosed Arenas

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ABSTRACT

Mott MacDonald has recently provided wind engineering services to stadium projects either originally designed as an enclosed stadium or redeveloped to introduce a new roof to form an enclosed stadium. One of the main challenges for enclosed stadia is achieving adequate ventilation and transparency to ensure health of natural turf. Ventilation and transparency also effect thermal comfort for spectators, noise emissions and internal reverberation. Transparency is achieved using light-weight roof cladding inclined to maximise turf irradiation. Ventilation openings effect internal pressure within the stadium, and the roof form and incline effects external pressures. Wind loads derived from correlation analysis of pressures across long-span roofs and drag on long-span structures are important to ensure cost effective design and can result in loads less than those derived from wind codes. This paper reviews these effects on the design of Canterbury Mixed Use Arena, otherwise known as Te Kaha.

1. Introduction

Te Kaha (Canterbury Multi-use Arena) is a significant project for the people of Canterbury. Te Kaha is uniquely positioned on an inner-city site on the eastern edge of the Christchurch CBD, which increases the importance of its function as an active, accessible, community-use venue and precinct on both event and non-event day.

Figure 1 Te Kaha, Christchurch, New Zealand (courtesy Populous, Developed Design Report)

The design fundamentals remained integral to the design approach, including:

- Rectangular permanent natural turf pitch, with a fully covered roof, with ETFE for turf health and a clear span.
- A capacity of 25,000 permanent seats in primary sports mode plus the ability to add 5,000 temporary seats in future. Event mode flexibility via a 35,000-person capacity for full size concerts in arena mode and up to 15,000 in a cut-down mode.
- Multi-use potential to not preclude the ability to host a range of events year-round, including expos, concerts, festivals, trade shows etc.

Six primary risks were identified as being turf health, ventilation, acoustics, programme, cost and urban design, with the design developed from the concept/business case, through schematic and developed design to determine the most optimum outcome.

The shape and form of the stadium are shown below in Figure 1, CGI (Computer Generated Image) of the arena, with the scale shown in Figure 2. It could be thought of as a large domed silo.

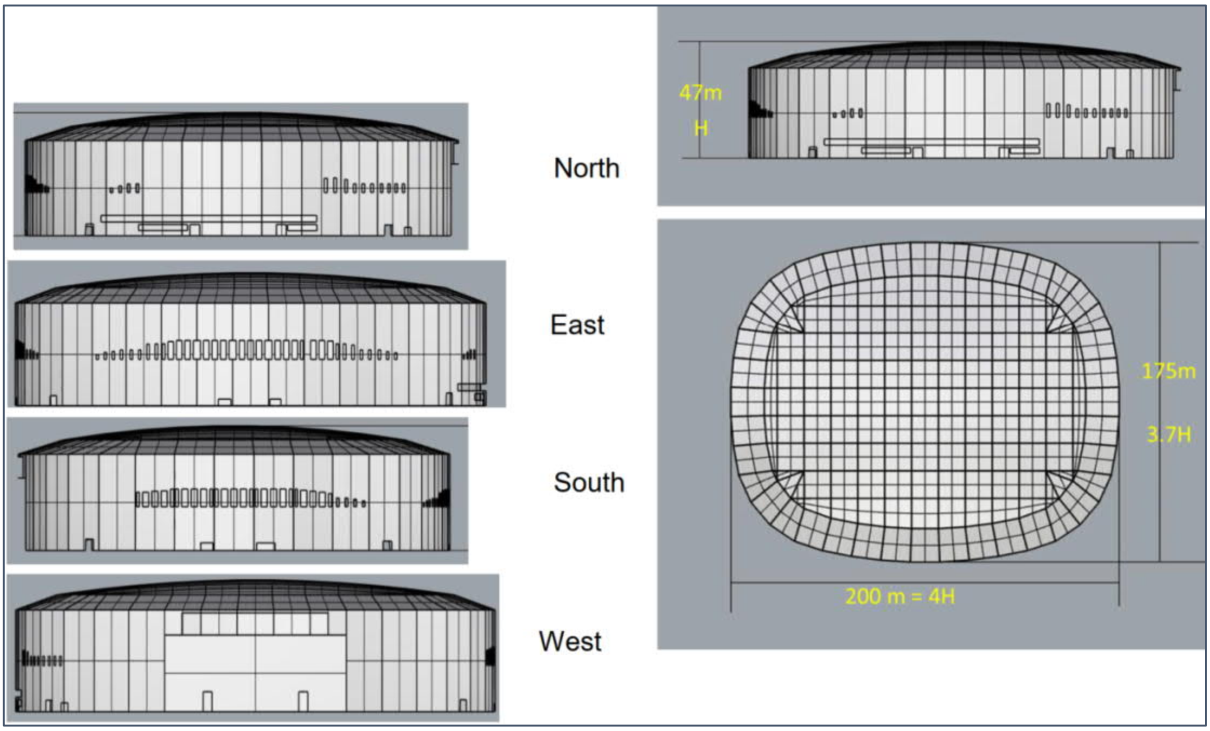


Figure 2 Scale and form of the proposed arena with louvre locations

2. Parametric Modelling Approach

A parametric modelling approach was used to inform a multicriteria analysis to determine the best option based on weighted performance metrics as shown below in Figure 3. The parametric modelling approach used Grasshopper as a scripting environment for Rhino, a 3D modeling software. Grasshopper is a visual programming tool that allows users to create parametric models and complex geometry using visual programming. The Grasshopper interface is built into Rhino and allows users to create and manipulate geometry using a graphical interface rather than writing code. Grasshopper also offers a wide range of plug-ins, called "components" that can be added to the interface to perform specific tasks, such as generating a mesh or creating a pattern. These components can be customized and manipulated to suit the user's needs. Specific components relevant to wind engineering include OpenFOAM (Computational Fluid Dynamics tool), Eddy3D, Butterfly or similar. Other components used include Ladybug and HoneyBee (for solar irradiation and thermal comfort) and Pachyderm (for acoustic analysis).

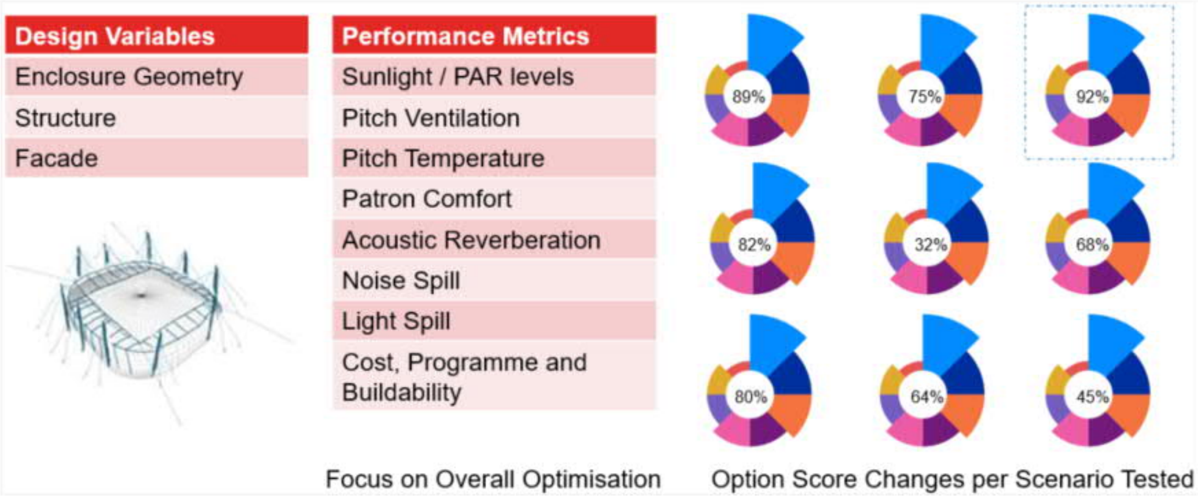


Figure 3 Multicriteria analysis, with performance metrics generated from a parametric analysis.

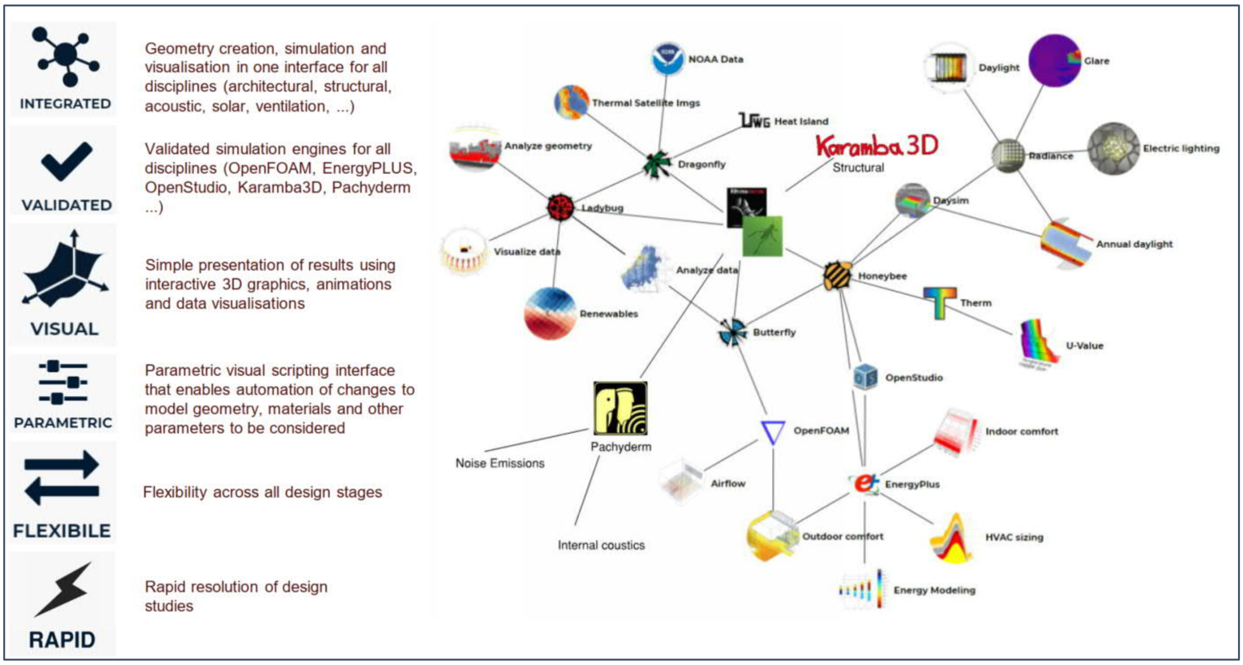


Figure 4 Parametric modelling approach using Grasshopper with Rhino

3. Wind Engineering Challenges

3.1 Code Based Assessment

The form of the stadium could be considered as a curved or mansard roof, as shown below in Figure 5, with parameters r/d ~0.05, h/d ~ 0.25, b/d ~1.0 and α ~ 30°. Predicted external pressure coefficients estimated from AS1170.2 vary from:

- Upwind (U): peak negative of -0.2 to -1.3, and peak positive of 0 to 0.4
- Central (T): peak negative of -0.5 to -0.8 and peak positive of 0.1 to 0.2 (for curved roof only)
- Downwind (D): peak negative of -0.2 to -0.6, and peak positive of ~0.2 (for curved roof only)

When combined with a site-specific wind speed at roof height of 49m/s (based on a synoptic profile) would give suction up to ~1.9kPa (upwind edge), and downward pressure of ~0.6kPa. With local pressure factors these could be 2-3 times greater or ~3.8kPa suction and 1.2kPa downward pressures.

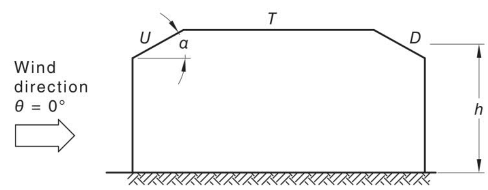
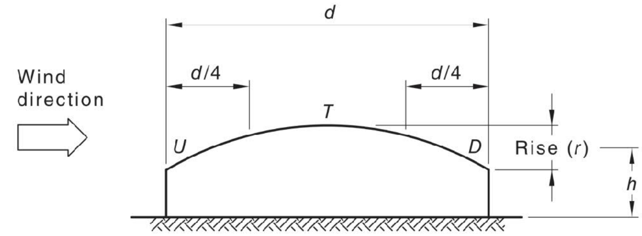
 C4: Mansard Roof Uses Clause 5.4.1, which suggests Table 5.3(B) and (C): U: --0.2,0.4; T and D = -0.6	 C3: Buildings with Curved Roofs For 0.1≤r/d≤0.2: U: -1.3,0; T=-0.8,+0.2; D=-0.6, +0.25 For r/d<0.1 uses Table 5.3(A) of AS1170.2 (which is only applicable for slopes less than 10°) giving: U: -0.9,-0.4 T=-0.5,+0.1; D=-0.2, +0.2

Figure 5 External Pressure Coefficients

3.2 Preliminary Loads Analysis

Computational Fluid Dynamics (CFD) was used to estimate preliminary loads, with the dimensions of the computational domain (set to a radius of 1000m and a height of 500m) chosen as a compromise between establishment of adequate free-field atmospheric boundary layer flow, resolution of surrounding structures and a manageable cell count (>10 million). The Deaves and Harris (1978) atmospheric boundary layer (ABL) model was implemented in OpenFOAM, closely following all recommendations of Richards and Hoxey (1993). The upper boundary turbulent gradients are also defined following the equations outlined in Sumner and Masson (2012). These equations were implemented for the k-epsilon class of turbulence models and the realizable k-epsilon model (Shih et. al. 1994) was used for the wind simulation. Validation of successful atmospheric boundary layer propagation was carried out using the test case domain size, grid velocity conditions and turbulent length scale reported in Hargreaves and Wright (2007). A steady Reynolds averaged simulation was then conducted for all eight cardinal directions, with the ABL reference velocity was set to 10m/s at a 10m height for all directions, and simulations run to convergence.

Mean pressure coefficients were derived as $\overline{C_p} = \bar{p}/(1/2\rho\bar{U}^2)$, where $\bar{p}$ is the mean pressure resolved from the CFD analysis relative to a mean wind $\bar{U}$ at reference height, shown below in Figure 6. Comparing these mean pressure coefficients to those from the code (quasi-steady) analysis suggests

- Upwind (U): peak negative of -0.5 to -1.0
- Central (T): peak negative of -0.25 to -0.5
- Downwind (D): peak negative of -0.0 to -0.5

This would suggest that a curved roof form is not an unreasonable assumption, though the code underestimates suction at the leading edge of the roof and separation at the trailing edge (better estimated by the mansard form). The mansard form significantly underestimated suction at the leading edge.

3.3 Ventilation for Pitch Health and Spectator Comfort and Code Compliance

Ventilation of the arena is required to ensure health of the natural turf, thermal comfort and adequate fresh air for spectators (to limit Carbon Dioxide, CO_2, concentration as per the New Zealand Building Code, NZBC). Louvres have been located on the façade as shown on the north and east elevations above, but also to the west. The brief for pitch health for cool season grasses (such as perennial ryegrass) prescribed:

- 10-20 °C for root growth (growth generally ceases below 5 °C)
- 15-25 °C for shoot growth (turf is stressed above 30 °C)
- Humidity ideally below 60% at 25 °C
- Air movement 6-8kph (1.7-2.2 m/s) to provide ventilation, cooling, humidity control

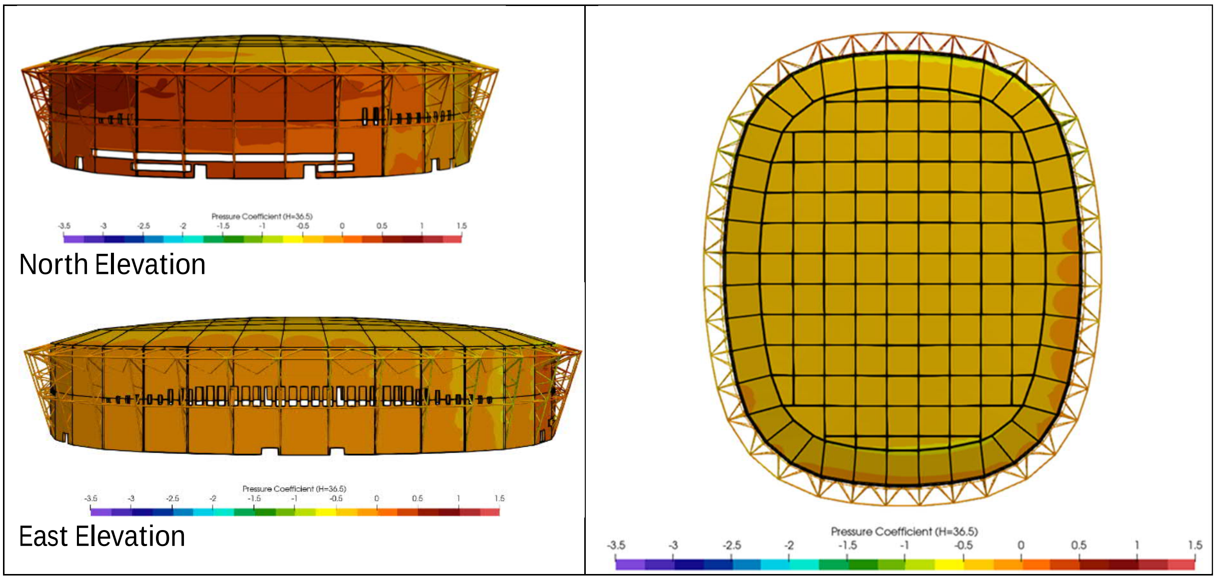


Figure 6 Pressure coefficients referenced to roof height

Winds from 8 directions were simulated using the CFD model outlined above and combined with local meteorology statistics to enable an estimate of the number of hours per year wind speeds were within a given range across the pitch. Wind speeds were predicted to exceed 1.7m/s less than 5% of hours per annum with the flow passing across the near side of the pitch, before rising to the west louvres as shown in Figure 7. Consequently, pitch ventilation fans were introduced and modelled using a transient analysis with the results presented below in Figure 8.

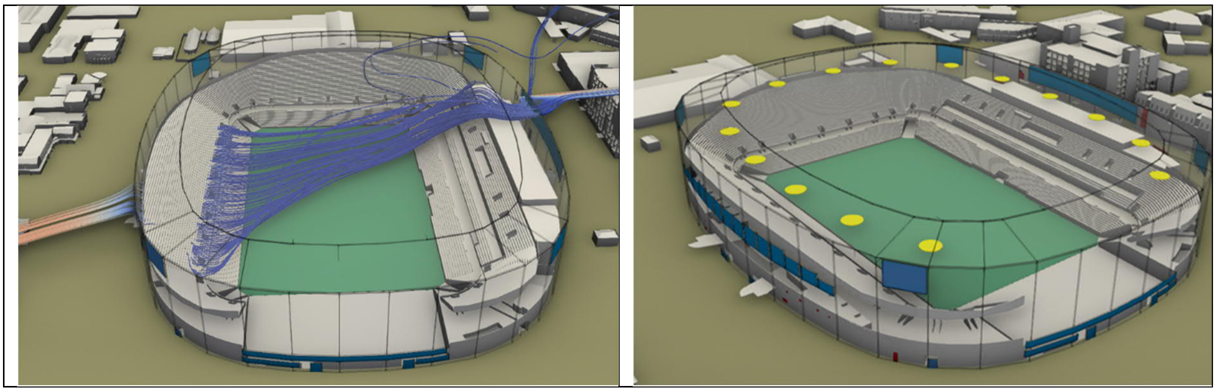


Figure 7 LEFT: Natural Ventilation; RIGHT: Large Diameter Ceiling Fans (LDCF)

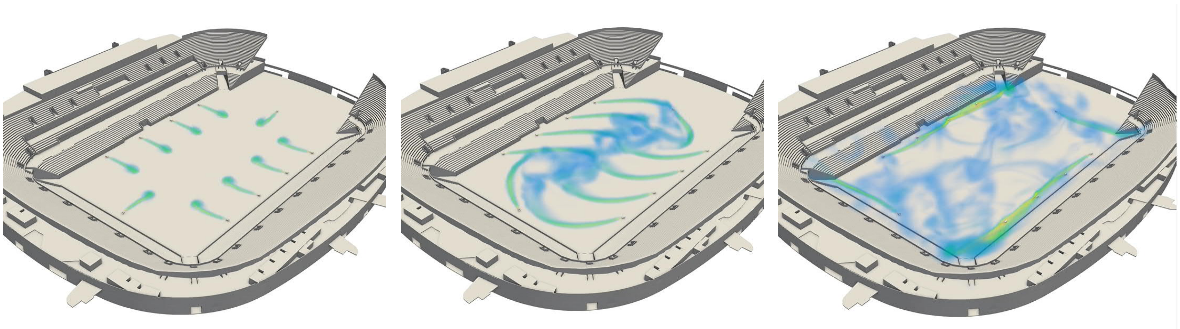


Figure 8 Transient analysis with rotating pitch-side fans

Bulk airflow modelling, using IESVE Apachesim (with Macroflo) was undertaken to assess predicted air flow rates through the façade and into the seating bowl. Impacts on ventilation rates, air temperature and CO_2 concentrations within the seating bowl and concourse spaces were assessed re compliance with the NZBC. Macroflo models bulk air movement between “zones” with buoyancy driven flow (stack effect) modelled by not only stratifying the volume (to properly reflect temperature stratification), but also the occupant heat load (ie. 1/3 of the heat load from occupants to the occupant zone, and 2/3 to the zone above) as noted by IES (2023).

There are various metrics for assessing thermal comfort, many of which have been outlined in Ghani et al (2022), Losi et al (2021) and in "Competition Medical Guidelines for World Athletics Series Events" by Adami et al (2020), including:

- UTCI (Universal Thermal Comfort Index),
- PMV (Predicted Mean Vote),
- WBGT (Wet Bulb Globe Temperature),
- SET (Standard Effective Temperature),
- PET (Physiological Equivalent Temperature) etc.

Adaptive Thermal Comfort (ATC) was proposed as the metric to be used as recommended by ASHRAE Standard 55 (2010) for naturally ventilated buildings. The bulk flow analysis predicted compliance with the ATC criteria for 50% of the time during summer months (though as noted this is likely to be conservative as stack effects are a challenge to model on an hourly basis). Large Diameter Ceiling Fans, LDCF, (or High-Volume Low Speed, HVLS) were proposed and modelled as shown below in Figure 7, to improve comfort as well as reduce CO_2 concentration which was also shown to be compromised.

3.4 Model Construction

The overall dimensions of the mixed-use arena (height, plan, shape, etc.) were constructed to within an accuracy of 2% while the surrounds were constructed to within an accuracy of 10%. The overall model was constructed at a scale of 1:200 using in two halves, with the truss sections for each part laser cut from 3 mm thick acrylic, erected on each baseboard, and clad with acrylic sheet to match the seating platforms. Openings in the bowl seating platforms were included, as were openings in the façade. The internal playing field made removable to allow access to tubes for connection to pressure transducers and inclusion of a volume to allow for Helmholtz resonance effects. Pressures were measured using taps mounted externally and internally.

Figure 9 Model Construction

3.5 Internal Resonance

As noted in Holmes (2015), the Helmholtz resonator is a well-established concept in acoustics (Rayleigh, 1896), which describes the response of small volumes to the fluctuating external pressures.

Although originally applied to the situation where the external pressures are caused by acoustic sources, it can be applied to the case of external wind pressures 'driving' the internal pressures within a building. Helmholtz resonance within building enclosures has largely been overlooked acoustically until recently with studies by Vinkor (2004) and Fernandez et al (2016) given the importance of their impact on infrasound noise from wind turbines. As noted by Vinkor, If the acoustic wavelength notably exceeds the resonator's dimensions, the air in and near the neck (a mass) moves compressing or expanding a spring (the air volume). If the air volume is V and the circular hole (or flanged cylindrical neck) has cross-sectional area A, the Helmholtz resonance frequency is given by the equation

$$f_H \approx \frac{c}{2\pi}\sqrt{\frac{A}{Vh_{eff}}} \tag{1}$$

Where the speed of sound in air, $c \approx 340m/s$, $h_{eff} = h + 0.8\sqrt{A}$, with h the neck length (wall/facade thickness). Lowest order room resonances can be calculated from $f_S = c/2L$, where L is the largest room dimension. Vinkor showed that for a typical residential room with an open window, f_S~34Hz and f_H~6 to 8Hz, which corresponds with blade pass frequencies from wind turbines.

In contrast, the first acoustic mode of Te Kaha is at ~0.85Hz (which as noted below coincides with a roof structural mode), and Holmes (2015) notes that the Helmholtz resonance frequency is:

$$f_H \approx 55\frac{A^{1/4}}{V_o^{1/2}[1+(K_A/K_B)]^{1/2}} \tag{2}$$

with A, the opening area, V_o, the internal volume, and K_A/K_B the ratio of the bulk modulus of air to the bulk modulus of the building (stiffness ratio). With a volume of ~10^6m^3, an area of ~500m^2, and a stiffness ratio of ~4 (arena with flexible roof) gives f_H~0.12Hz, increasing to 0.24Hz with a reduction in the stiffness ratio to 0.2. These frequencies are well below the acoustic mode, and don't coincide with a structural mode.

An open area/volume factor is included in AS1170.2 (and differs from the reduction factor for large volume buildings in ASCE 7-5 as noted by Holmes and Ginger (2009)) to be applied when the largest open area in a building is on a wall, and the open area is greater than the total open area on the roof and other wall surfaces by a factor of 6 or more. This accounts for resonance effects as noted above.

3.6 Approach Flow – Synoptic or Downburst

Low rise buildings such as stadia and industrial buildings, masts/towers etc are affected by downdraft winds more so than synoptic winds. Downdraft gust wind profiles have been included in ISO 4354, but turbulence intensity profiles remain uncertain. Where extreme events are driven by downdrafts, it is important to include appropriate profiles for design and testing (as has been done for other projects such as Stadium Australia and Light Towers). NIWA confirmed that extreme wind speeds are dominated by synoptic rather than thunderstorm events, hence a conventional boundary layer profile with mean wind speed and turbulence intensity (as well as turbulence length scale) was used.

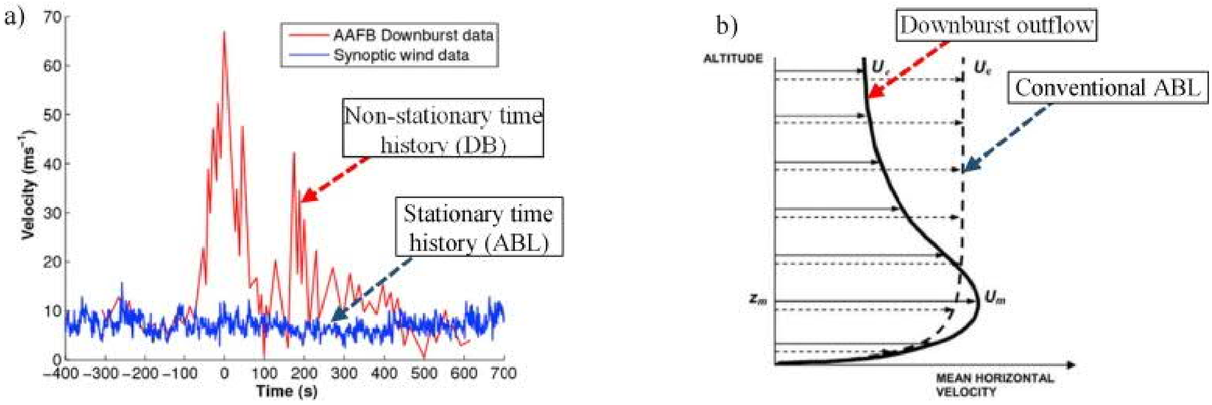


Figure 10 Downburst and Synoptic Profiles

3.7 Structural Form and Dynamic Response

The roof structure spans ~175m by ~200m and supports the roof façade and wall cladding to provide enclosure to the arena, while being separated from the bowl to allow for movement during seismic events, as shown below in Figure 11. The overall roof form can be considered as a collection of key components, which include radial columns and trusses, Oculus ring truss, Halo ring truss, Roof diaphragm, Oculus truss and vertical bracing. A dynamic analysis (modal analysis) was carried out by our structural engineering team, with the lowest modes responding longitudinally (north-south) and laterally (east-west) at about 0.65 Hz, with vertical roof modes activated at about 0.8Hz.

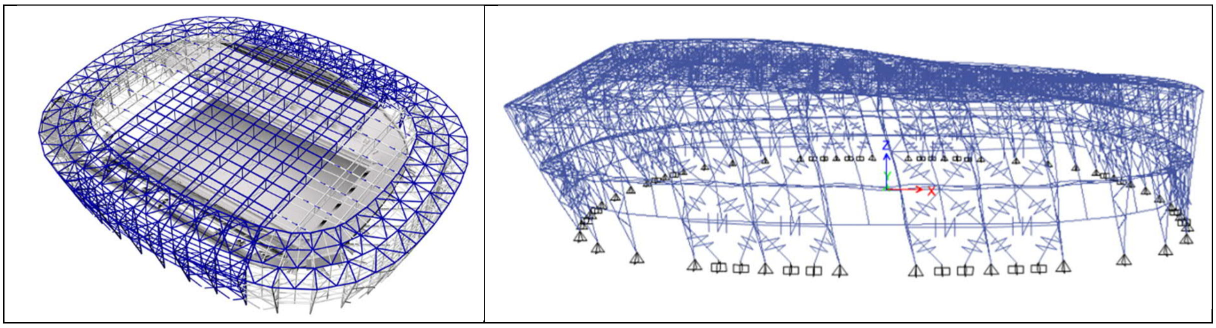


Figure 11 Structural Form and Modal Analysis

3.5 Structural Loads Analysis

The load-response correlation (LRC) method derived by Kasperski and Nieman (1992) defines an effective pressure distribution, $C_{p_{eff}}$ an Nx1 vector, considering the correlation of the fluctuating pressure over the whole structure, and provides maximum or minimum load effects using influence coefficients:

$$\left\{C_{p_{eff}}\right\}_{F_{max,min}} = \left\{C_{p_{mean}}\right\} \pm g_r \left[\sigma_{C_p}\right] \left\{\rho_{F,p}\right\} \quad (3)$$

with $C_{p_{mean}}$ an Nx1 vector of mean pressure coefficients, g_r is the peak factor (taken as 4.0), σ_{C_p} is an NxN diagonal matrix of the standard deviation of pressure coefficients, $\rho_{F,p}$ an Nx1 vector of correlation coefficients relating the pressures to an overall response. The overall load on the structure, F, can then be obtained from the effective pressure and influence coefficients as follows:

$$F_{max,min} = q_h \left\{C_{p,eff}\right\}^T [A]\{I\} \quad (4)$$

with q_h the dynamic pressure (mean at roof height or the reference height of pressure coefficients), A an NxN diagonal matrix of panel areas, and I an Nx1 vector of influence coefficients relating the pressure at one location to the reaction at another location (eg. Uplift or drag force).

Using this approach, the maximum uplift on the roof was estimated as ~20MN compared with a peak of ~45MN. Likewise, the drag (lateral/longitudinal) force was estimated as ~4MN compared with a peak of ~8MN (assuming a code approach using a "silo/circular bin"). Refer to Figure 12.

Holmes et al (1997), "Wind Loading and Response of Large Stadium Roofs", provides a method for estimating resonant loads by:

- Weighting the measured pressure coefficients by the two-dimensional mode shapes
- Modal-weighted pressures are then spectrally analysed to determine the spectral density of each modal force around the natural frequency of each mode.
- Calculate the deflection and acceleration response using random vibration theory
- Determine the equivalent static load distribution for resonant loading based on the inertial load (ie. Modal mass times acceleration divided by the area to obtain pressure)

Using this approach, the dynamic response factor for most panels was determined to be less than 1.1 (10% contribution to structural loads from dynamic effects).

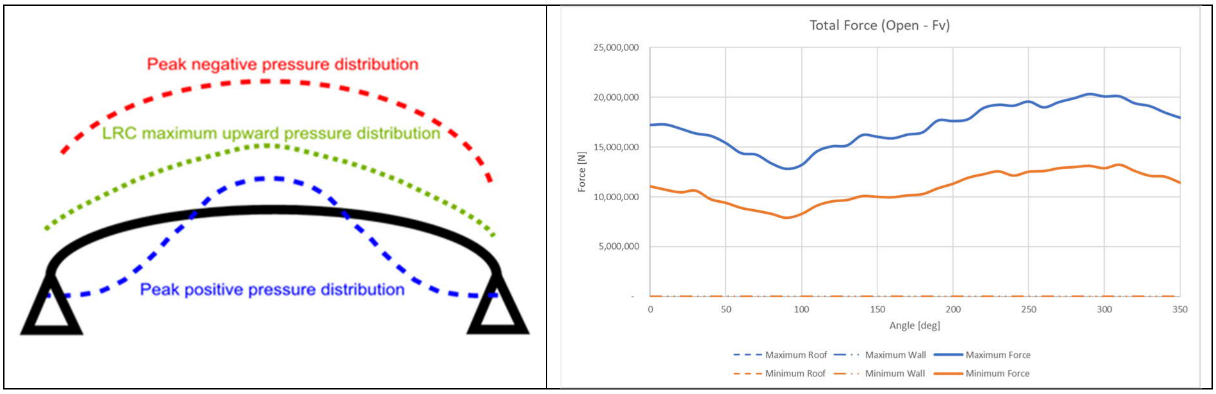


Figure 12 LRC Approach (LEFT); Resultant Overall Vertical Force (RIGHT).

3.6 Other Aspects

Fatigue life of critical connections and was an important issue for Etihad Stadium, with wind induced dynamic response of the cantilevered roof causing fatigue of some members. Additionally, the assessment of deflections due to the aerodynamic response of the structure is an important consideration. Assessment of required velocities and locations of exhausts and intakes to prevent re-ingestion of fumes and accumulation of fumes within occupied spaces. Wind effects on play can be significant. ETFE cladding is often used and formed using pressurized pillows, which can redistribute peak pressures across the pillow for long spans, hence time traces of pressures either side of the pillow are required for detailed design.

4. Conclusions

Large naturally ventilated, enclosed arenas provide many challenges to the design team across various disciplines with parametric modelling tools useful to understand key parameters affecting the design. Bulk flow analysis using energy simulation tools require should be compared to more detailed computational fluid dynamics (CFD) models for scenarios. Interpretation of wind codes relative to building forms can lead to errors in design loads for unusual, shaped buildings with CFD a useful tool to clarify assumptions and provide preliminary loads. Much conjecture still exists regarding appropriate thermal comfort indices for spectators and performers, and while solar irradiation is well understood for turf health, turf ventilation requirements is less so. Internal acoustic resonance can be excited by wind and couple with structural modes of vibration and should not be discounted. Lack of correlation of pressures across long span roofs and around stadium facades can results in significant reduction in structural loads.

5. Acknowledgements

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