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Wind and Heat Modelling for Stadia

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Abstract

Ensuring adequate patron comfort and pitch health is achieved, and minimising wind effects on play are critical in the design of stadia. Failures in these three areas can lead to under-utilisation of the stadium and increased management costs. Similarly pollution dispersion into the audience and surrounds can be detrimental to individuals' safety and comfort. This paper will discuss the use of computational fluid dynamics and wind tunnel testing to improve patron comfort, stadium operability, and explore cost savings through structural optimisation on the redevelopment of ASB Tennis Arena and the design of the new Western Sydney Stadium.

Introduction

Aurecon, Building Sciences recently provided wind engineering services for the redevelopment of ASB Tennis Arena (ASB) (figure 1) and the under-construction Western Sydney Stadium (WSS) (figure 2). The $16.5 million redevelopment of ASB in Auckland New Zealand involved upgrading existing outdoor seating to covered grandstands and site works to incorporate the many elements of the facility into a cohesive sporting venue. WSS is a new $300 million rugby stadium in Parramatta, Australia with a seating capacity of 30,000. Wind engineering studies were conducted for wind effects on play, patron comfort, pitch health, pollution dispersion and structural optimisation.

Figure 1. Computer generated image of ASB Tennis Arena (image provided by Jasmax, 2017)

Figure 2. Computer generated image of Western Sydney Stadium (image provided by Populous, 2017)

Computational Fluid Dynamics Implementation

Aurecon have implemented the Deaves and Harris [14] atmospheric boundary layer (ABL) model in OpenFOAM, closely following all recommendations of Richards and Hoxey [24] including upper boundary shear stress. The upper boundary turbulent gradients are also defined [33]. These equations were implemented for the k-epsilon class of turbulence models and the realizable k-epsilon model [30] was used for the wind simulations.

Steady Reynolds averaged simulations were conducted for all eight cardinal directions. The ABL reference velocity was set to 10m/s at a 10m height for all directions. Simulations were run to convergence where three sampled velocity points distributed throughout the domain converged to steady state. Computational Fluid Dynamics (CFD) results were then post-processed using a Weibull distribution.

Ansys CFX was used for patron comfort and wind effects on play for ASB and rain intrusion modelling for both stadia. OpenFOAM was used for all other CFD studies discussed in this paper.

Patron Comfort

Assessment of pedestrian wind comfort and safety requires comparison of predicted pedestrian level wind speeds against comfort and safety criteria. Criterion wind speeds are those which should not be exceeded more than a specified percentage of time annually. See Jones [22] for a detailed discussion of Aurecon's environmental wind assessment method.

The Lawson/Davenport criteria [19,23] are often used for wind comfort and safety assessments in outdoor areas. The Lawson/Davenport criteria are used to assess wind force only and do not allow for variations in ambient temperature, solar irradiance, and other environmental variables. The comfort criteria are based on the exceedance of the threshold wind speeds occurring less than 5% of the time (approximately once every week during daylight hours [25]). The value of 5% has been established as giving a reasonable allowance for extreme and relatively infrequent winds that are tolerable within each category. For the safety criteria, the threshold mean hourly wind speed is not to be exceeded more than once per annum during daylight hours, which equates to an annual threshold exceedance of 0.023 %.

The patron comfort analyses for ASB and WSS were conducted in Ansys CFX and OpenFOAM respectively. A statistical analysis of historical meteorological data was performed to represent the relative frequency of measured wind speeds by a Weibull [7] distribution. A type 1 Gumbell [18] extreme value distribution, with the Gringorten correction [18] can be used for determining the environmental wind speeds used in the safety assessment.

Rain Intrusion

Unlike the assessment of pedestrian-level wind speeds, there is no established criteria for assessment of rainfall intrusion for pedestrian comfort and safety. Criteria for this assessment were obtained by converting American Meteorological Society (AMS) [1] rainfall intensity classifications (table 1, units of mm/hr) into a measure of rain capture rate (units of $kg/m^2.s$) for direct application to CFD results.

Classification	Rainfall intensity (mm/hour)	Corresponding capture rate ($kg/m^2.s$)
Light rain	< 2.5	<0.0007
Moderate rain	2.6 to 7.6	>0.0007 & <0.002
Heavy rain	>7.6	>0.002

Table 1. AMS rainfall intensity classifications and corresponding capture rate.

Modelling of wind driven rain is a multiphase simulation consisting of a continuous phase (air) and a discrete phase (water droplets). Rain droplets are injected and dispersed into the continuous phase. Droplet trajectories are influenced by momentum of the continuous phase. The Lagrangian particle tracking method was used to model the trajectory of rain droplets. Gravity and drag forces were applied to the particles in order to accurately model the droplets' trajectory. A Rain droplet diameter of 1.5mm and corresponding droplet terminal velocity of 5.4 m/s were used for the analyses based on literature [26].

Analyses of ASB were performed for eight proposed designs to determine the effect of a raked western roof on patron comfort and investigate the feasibility of extending the roof (figure 1) to prevent rain intrusion.

Wind Effects on Play

A concern for the owners of both stadia was wind effects on play. The patron comfort CFD assessment was extended to include effects on play with research conducted to determine suitable acceptance criteria.

Tennis

Neither the International Tennis Federation, nor the Association of Tennis Professionals specify guidelines for on-court wind conditions. However, the Intercollegiate Tennis Association of the USA stipulates that games should not be played outside for wind speeds of more than 20 mph (9 m/s) [20]. Therefore, on-court wind speeds of 9 m/s or greater are indicative of 'extreme conditions' and on-court performance is affected by lower wind speeds. A performance criterion wind speed of 15 mph (6 m/s) was selected based on interpretation of the Lawson/Davenport comfort criterion and player feedback [34].

Rugby

Limited data is available on wind effects on a rugby ball's flight, however contributions from Alam et al., Ball, and Djamovski et al., [1,8,15] give some guidance on the possible effects of crosswind. A simple calculation of a ball's lateral displacement was conducted for a typical rugby punt using reported drag coefficients [1]. For a 6m/s crosswind a typical 45m field goal punt was found to have a lateral displacement of 2m. Similar calculations for crosswinds of 10 and 15m/s result in lateral-displacements of 4.7m and 12.5m, respectively.

Assessment criteria however are difficult to define, since crosswind effects are not necessarily detrimental to play and may in fact be used to advantage by players and coaches [13]. The probability of exceeding 6m/s at varying heights above the playing field was reported.

Pitch Health

Pitch health is also an important factor in stadia effects on play and visual enjoyment of patrons. Pitch health depends on a multitude of factors including but not limited to light, water, ventilation, and soil type. For WSS, Aurecon analysed solar access and air movement over the pitch to inform likely growth conditions. Adequate ventilation and solar access are both critical to the quality of the grass on the pitch (termed turfgrass herein) of a partially enclosed stadium. Without which the turfgrass has the potential to have a short life, limited growth (root development), and/or is sparse and disease ridden.

Air Movement

Proper air movement is critical for maintenance of turfgrass in reduced lighting situations. Air movement provides CO_2 to the plants for photosynthesis and enhances the reduced rate of evapotranspiration in reduced light situations, important for maintaining turfgrass plant turgidity [29]. Without proper turfgrass turgidity the quality of cutting can decrease causing matted turf which traps moisture and serves as suitable environment for turf diseases [29]. Air movement is also important to remove free surface moisture following irrigation or dew, as free surface moisture facilitates several turf diseases [29]. Rogers et al. [29] state that the desired air movement over the playing surface is between 1 and 2 m/s.

Light

Light energy is converted by the turfgrass to starches and sugars during photosynthesis. Without adequate light the turfgrass even in a non-trafficked situation will eventually die. Turfgrass death is greatly accelerated in a sports field situation.

Solar energy contains a wide spectrum of light energy from infrared through to ultraviolet. However, only a portion of this light is suitable for photosynthesis in plants. This portion, which amounts to approximately 45% of the total energy received from the sun, is referred to as Photosynthetically Active Radiation (PAR) and coincides reasonably well with the visible portion of the spectrum [16]. There are approximately 2 moles of photosynthetically active photons per MJ of solar radiation [17]. Hence by predicting the amount of solar radiation received onto the grass surface, the equivalent PAR value can be obtained.

Average daily radiation for each month was predicted with the Grasshopper plugin, Ladybug. Figure 3 shows the mean daily PAR for August with associated sun paths. Note that asymmetrical distribution with the north and west turfgrass receiving less daily PAR than other areas. Further discussion on solar radiation modelling methods follows in the section on thermal comfort.

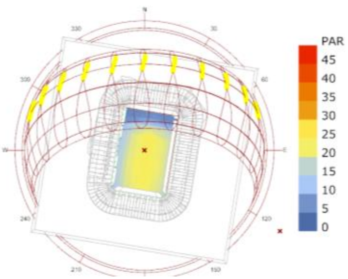

Figure 3. Estimated mean daily PAR for August.

Thermal Comfort

Thermal comfort was assessed using the Universal Thermal Comfort Index (UTCI). The UTCI is an outdoor thermal comfort index that takes into account air temperature, wind speeds, relative humidity, and the mean radiant temperature. The UTCI equation is a sixth order multivariate polynomial that was developed from regression analyses of extensive modelling using Fiala's multi-node human physiology thermal comfort model whilst considering people's clothing behaviours [12]. The UTCI output is a compensated temperature in degrees Celsius with corresponding thermal stress categories. The goal UTCI temperature range for no thermal stress is between 9°C and 26°C. The UTCI was chosen as the comfort index as it is very sensitive to changes in conditions (temperature, solar irradiance, wind and humidity) and represents variability of thermal conditions with time better than other indices [9]. It is also independent of an individual's characteristics (gender, age, weight, clothing, etc.) providing a mean approximation of the population's comfort [11].

Modelling Methods

Thermal comfort was assessed for the open and enclosed stadium configurations for ASB. The open configuration is the standard operating mode (figure 1), in the enclosed configuration temporary screens are erected and the retractable roof is closed to prevent rain intrusion.

For the open configuration CFD and heat transfer analyses were conducted in OpenFOAM and Ladybug respectively. The analyses were conducted for four times of day during peak international event season.

Solar adjusted mean radiant temperatures were calculated at 1.5m x 1.5m grid points on the seating areas using the SolarCal method [3] implemented in the toolchain developed by Mackey [24]. Solar irradiance data was used to develop numerical sky models in conjunction with Grasshopper's inbuilt raytracing capabilities to determine view factors used in the heat transfer calculations that account for shading from the CAD geometry.

The 50th percentile wind speeds for each analysis period were calculated in OpenFOAM and sampled at the previously defined grid points. The sixth order multivariate UTCI polynomial was solved spatially for all the hours within the analyses periods. The mean UTCI for each grid point was then calculated for each period and used to create several 2D contours to represent the thermal comfort in 3D space (figure 4).

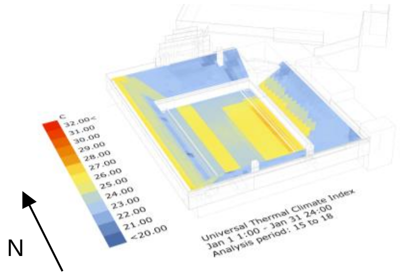

Figure 4. 3D visualisation of the mean UTCI temperatures in degrees Celsius for January 3pm – 6pm for ASB. ASB's roof is not displayed for clarity.

Pollution Dispersion

Different pollutants were of interest for each stadia. For ASB the CO_2 concentration and the ventilation rate of the enclosed mode were assessed using Ansys CFX to advise on patron comfort within the space. Buoyancy effects were modelled with heat addition from people [10], stadium sports lighting, and solar loads through the retractable ETFE membrane and main roof included. Heat addition through the main roof was calculated using the cooling load temperature difference method. Heat loads through the ETFE membrane were assessed using Ladybug/Honeybee's daylight analysis tools accounting for the ETFE membrane's transmissibility. CO_2 emission area sources were defined at all major seating areas. Each patron was defined as emitting 0.01 g/s of CO_2.

CO_2 concentrations in practice never reach unsafe levels in typical buildings (greater than 5000ppm) [5]. However CO_2 levels can be used as an indicator of odours and patron acceptance of these odours within a space [5]. A CO_2 concentration threshold of 1000ppm was used as the acceptance criteria. Not exceeding this threshold will satisfy the majority of patrons entering the space with respect to body odour [5].

Kitchen exhaust odour and flare air pollution emissions were assessed for WSS. Items of concern were airborne grease and odour from the kitchen exhaust and CO_2 and particulate matter from flares.

Cladding Pressures and Structural Optimisation

Wind tunnel testing of both stadia were conducted against the requirements of AS1170.2 [31,32], the Australasian Wind Engineering Society QAM-1-1994 [6], and the ASCE Manual of Practice No. 67 for Wind Tunnel Testing of Buildings and Structures [4].

The wind tunnel tests were performed at the University of Sydney's atmospheric boundary layer wind tunnel. This tunnel has a cross-section of approximately 4.5m^2, a 2.3m diameter turntable and a development length of about 15m. The turbulent boundary layer is established using a trip board, spires and roughness elements over a development length (or fetch). The 1:200 scale model of WSS can be seen in figure 3, the average pressure tap density was greater than per 50 m² and additional taps were added to critical areas as required.

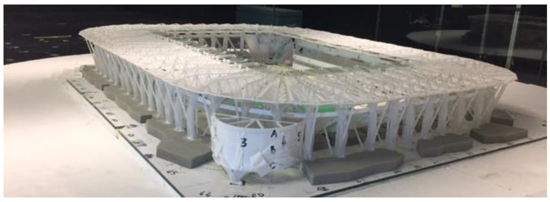

Figure 3. 1:200 wind tunnel model of Western Sydney Stadium instrumented with over 600 pressure taps.

Cladding Pressures

Net (or differential) pressures were determined by subtracting the inner (down) pressure coefficient from the outer (up) pressure coefficient at each time step of the data time series, and determining the peak net pressure coefficient from this new time series. The reference velocity was taken at 100m elevation. The sign convention for the pressure coefficients follows the convention in AS/NZS 1170.2 [31,32], namely positive is into the structure. A negative pressure coefficient indicates a suction on the upper surface of the roof. The dynamic mean and gust multipliers were derived from AS/NZS 1170.2:1989 [31] and AS/NZS 1170.2:2011 [32] respectively. ASB was defined as having surrounding terrain of category (TC) 3 and 4, whilst WSS's surrounding terrain was defined as TC3.

The peak (or extreme) maximum and minimum pressure coefficients were calculated using the up-crossing technique [7]. Rofail and Kwok [28] state that this provides the most repeatable peak values given a probability of exceedance. A 3 second gust per hour probability of exceedance (or 0.000833) was used for the analysis.

Load Response Correlation

Peak pressures derived from measured pressure coefficients occur locally for small areas and should not be considered for the design of primary structural members (but must be considered for the design of cladding and local support structure). Application of these peak loads to the structure simultaneously to perform analysis of structural members could produce an uneconomic design. The load-response correlation (LRC) method [21] defines an effective pressure distribution, taking into account the correlation of the fluctuating pressure over the whole structure, and provides maximum or minimum load effects using influence coefficients

Several response scenarios were investigated as requested by the Aurecon structural team including:

- Moments about the column supporting the truss, or tension/compression in the under-stay (or back-stay).
- Vertical load (up/down) on the ETFE membrane and the fabric PTFE membrane.

- Lateral or drag load on each truss.
- Differential pressures between adjacent fabric bays.
- Effect of localized bay failure on surrounding members.

Conclusion

A brief summary of the Aurecon's recent involvement in stadia design has been given, including both CFD and wind tunnel studies. Our work demonstrates the benefits of using computational models together with physical models to assess a broad range of issues affecting stadium design and optimisation.

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