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Wind loads on roof of the North Queensland Stadium

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ABSTRACT

A wind tunnel model study on the proposed, North Queensland Stadium (The Stadium) showed the largest net pressure occurs at the leading edge on the panels at the NE tail (Panels 32-38). The pressures on the panels are similar to the net pressures on an open roof given in AS/NZS1170.2. Shielding from the stadium results in significantly lower net pressures on the roof on other parts of the stadium.

1. Introduction

The Cyclone Testing Station at James Cook University was commissioned, to carry out a wind-tunnel model study to determine design wind loads for the proposed Stadium located in Townsville. Townsville is in a region subject to tropical cyclones, and hence wind loading is critical for the structural design of all elements of the Stadium

The Stadium will comprise a 130m × 80m football pitch area, a horse-shoe shaped, tiered spectator seating bowl with a 1 to 3m gap between the top tier and the complex 30m high roof covering the seating. A large scoreboard is located at the N-NE end, at the entrance to the Stadium. The modelled roof consists of thirty eight Panels and triangular ribs that flare out to the back of the stadium as shown in Figure 1. The enclosed building portion is on the Western side below roof Panel #s 3 to 9. The roof structure comprises columns and "cantilevered" roof trusses that support the panels and ribs.

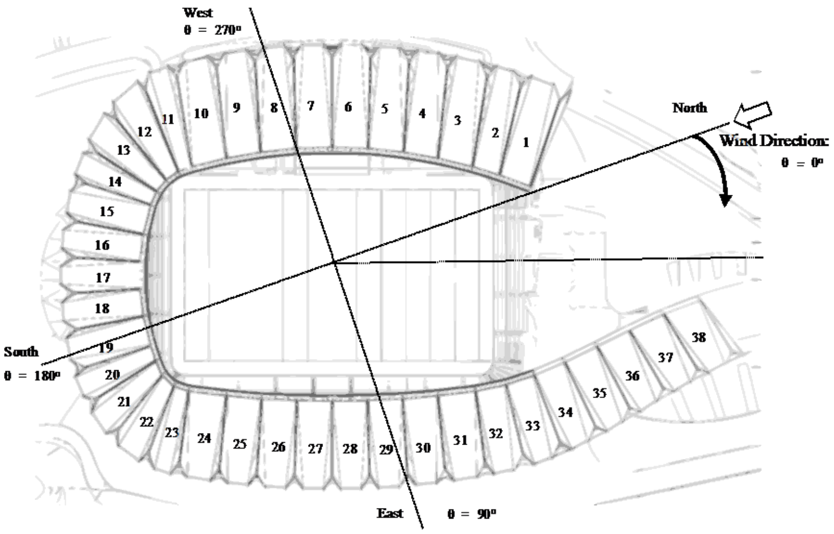

Figure 1. NQ Stadium roof layout diagram (as tested) and approach wind directions

In the following, the wind-tunnel testing approach and the main results for the roof loading are summarized. The wind loads on the roof are also compared to data available from, AS/NZS 1170.2 and other relevant studies (Ginger, 2003; Killen & Letchford, 2001; Letchford & Killen, 2002).

2. Wind-tunnel test procedure

An approach wind flow, equivalent to Terrain Category 3 (TC3) in AS/NZS 1170.2 (Standards Australia, 2011-2016), was simulated to a model scale of 1/300 in the JCU-CTS boundary-layer wind tunnel. There was good agreement between the measured mean velocity and turbulence intensity and the profiles for TC3 in AS/NZS1170.2, for the terrain simulation. The wind speed in the wind tunnel gives a model to full-scale velocity ratio of approximately 1/5. With the length scaling ratio of 1/300, this results in a time ratio of 1/60.

- *Stadium Model*

A 1/300 scale model of the NQ Stadium was constructed and mounted on the wind-tunnel turntable as shown in Figure 2. Six hundred and seventy five pressure taps were installed on the top and bottom surfaces of the roof panels and ribs. Tuned 1000 mm long, 1.5mm diameter, flexible tubing linked the taps to pressure transducers in the Turbulent Flow Instruments (TFI) system. Pressures were measured simultaneously on the top and bottom surfaces of the roof for winds approaching from $\theta = 0^{o}$ to 360°, in intervals of 5^{o}, shown in Figure 1. The pressure signals were recorded at 500 Hz for 10 sec (equivalent to 10 mins in full scale).

Figure 2. NQ Stadium 1/300 scale model in the wind tunnel

Pressure measurements at the taps were used to calculate the design pressures and were also used to determine design load effects on the roof structure. Positive (negative) pressures are defined acting towards (away) from a surface. Net pressures on the roof are defined as (top-bottom) surface pressures. All pressures have been converted to coefficient form by dividing by the mean dynamic pressure at 100mm (i.e. 30m in full-scale), the reference height: $C_p(t) = p(t) / (\frac{1}{2}\rho \overline{U}_h^{\,2})$. Here, $p(t)$ is the pressure varying with time t, ρ is the density of air and $\overline{U}_h$ is the mean velocity, averaged over 10 mins in full scale, at the reference height of h = 100mm (i.e. 30m in full-scale).

Five pressure records of 10 sec duration each (approximately 10 mins in full-scale) were collected at each tap, for each approach wind direction. Statistical analysis was carried out on the fluctuating pressures to get the mean, standard deviation and peak (maximum and minimum) pressure coefficients: $C_{\bar{p}}$, C_{σ_p}, $C_{\hat{p}}$, $C_{\check{p}}$. Averaged values from the five runs are given in the results presented.

3. Wind loads on roof panels and ribs

The aerodynamic shape factors given in AS/NZS1170.2 are then equivalent to peak pressure coefficients derived from the wind tunnel: $C_{fig} \times G_U^2 = C_{peak}$, where the velocity gust factor $G_U = (V_{des,\theta} / \overline{U}_h)$ = 1.68 is the ratio of the gust wind velocity to the 10-minute mean wind velocity at the reference roof height (30m).

- *Area-averaged pressures*

The variation of area-averaged maximum and minimum, net (top-bottom) pressure coefficients on Panel #s 8, 17, 22, and 33 and their ribs are given in Figures 3a-d. These figures show the panels and ribs experience negative net pressures when the wind blows towards the edge inside the stadium whilst the downwards loads are experienced when the winds approach from outside the Stadium. Large net upward pressures are experienced by the flat Panel #33 (at the tail of the roof) for NW winds (θ = 320°). These pressures are similar in magnitude to those obtained by Ginger (2003), Killen & Letchford (2001) and Letchford & Killen (2002). The equivalent $C_{fig,n}$:-3.00/1.68^2 = -1.07 and +1.05/1.68^2 = +0.37 are similar to the values given for the blocked-under case in Table D4(A) AS/NZS1170.2 . Lower loads are experienced by flat Panel #s 8, 17 and 22 which are shielded for winds approaching its edge inside the Stadium. The ribs experiences high positive and negative net pressures at normal wind directions that contribute to the global shear/drag force on the stadium roof.

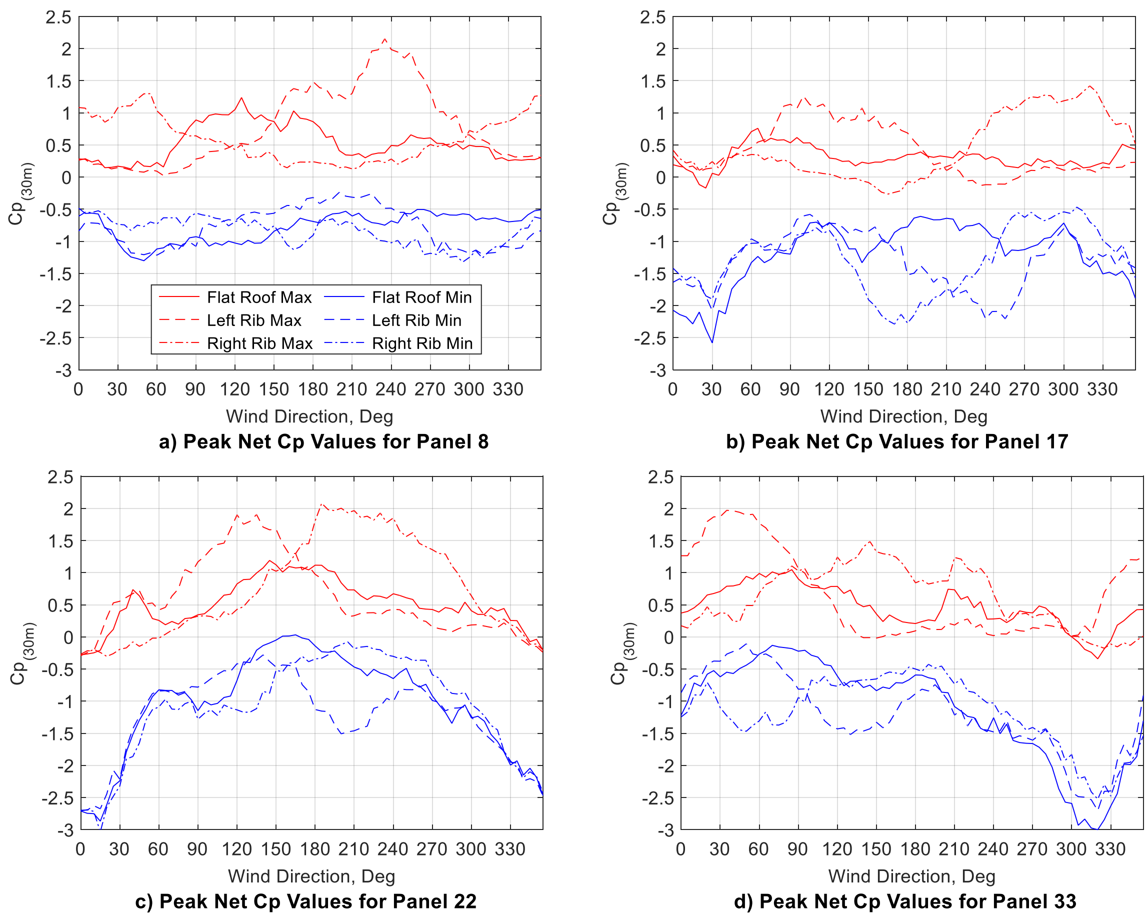

Figure 3. Area averaged Net C_{peak} on Panel #s 8, 17, 22 and 33 vs wind direction

- *Point pressures*

The variation of maximum and minimum, net (top-bottom) point pressure coefficients on the Taps 1 - 5 along the flat Panels 22 and 33 are given in Figure 4 , the corresponding equivalent C_{fig} values and wind direction are given in Tables 1a and 1b. Large upward loads are experienced when the wind blows towards the edge inside the Stadium (θ ~ 310° - 320° for Panel 33, and θ ~ 5° - 15° for Panel #22). Large downward loads are experienced when the wind blows towards the outside edge of the stadium roof (θ ~ 60° for Panel 33, θ ~ 200° for Panel 22). The equivalent peak net pressure coefficients (Net C_{peak}) at the leading edge derived from Table D4(A) AS/NZS1170.2 with K_l = 2.0 is -6.20.

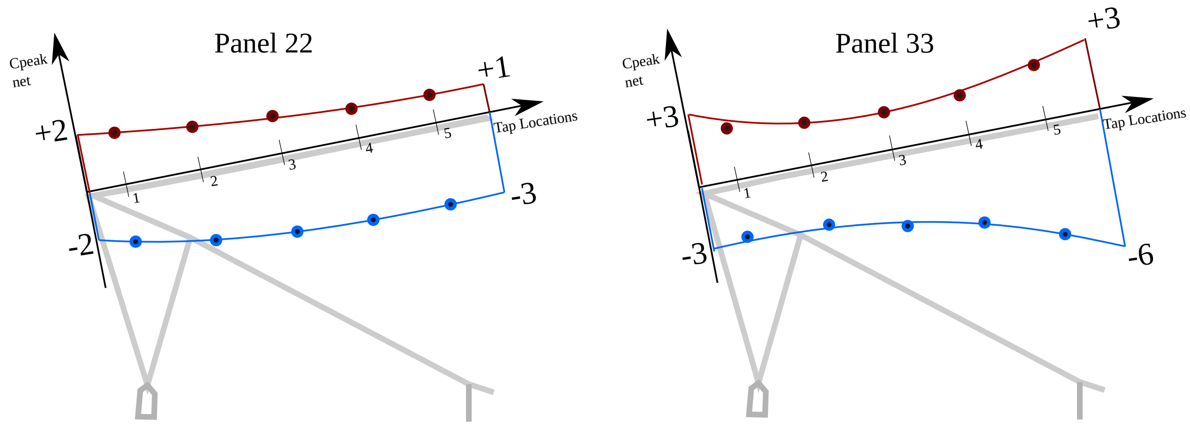

Figure 4. Net C_{peak} – Section views of grandstand showing worst-case positive and negative net pressure coefficients, considering all wind directions, measured on five tap locations on Panels 22 and 33

Table 1a. Equivalent $C_{fig,n}$s on Panel #22, with the corresponding wind direction in brackets.

Tap No.	**1**	**2**	**3**	**4**	**5**
C_{fig} +ve	0.75 (220°)	0.71 (185°)	0.56 (250°)	0.49 (145°)	0.49 (40°)
C_{fig} -ve	-0.89 (135°)	-1.04 (15°)	-1.19 (15°)	-1.14 (15°)	-1.20 (5°)

Table 1b. Equivalent $C_{fig,n}$s on Panel #33, with the corresponding wind direction in brackets.

Tap No.	**1**	**2**	**3**	**4**	**5**
C_{fig} +ve	0.83 (45°)	0.61 (50°)	0.53 (70°)	0.53 (80°)	0.73 (205°)
C_{fig} -ve	-0.97 (120°)	-0.95 (320°)	-1.22 (310°)	-1.41 (320°)	-1.83 (320°)

4. Structural Load Effects

The trusses supporting the roof were grouped into separate zones: East, West, South and NE and NW ends.

Wind load effects for designing the structure supporting roof were calculated using net pressures on the tributary area supporting the part of the roof by applying Equation (1).

$$X(t) = \sum_{j=1}^{N} p_j(t)\beta_j A_j \quad (1)$$

β_j is an influence coefficient for load applied at pressure tap (or patch) location, *j;* A_j is a tributary area for pressure tap (or patch), *j;* *N*- is the number of pressure taps or patches affecting the load effect being considered, and $p_j(t)$ is the time-varying pressure at tap or patch *j* at time *t*.

The load effects for every truss in each zone were determined by repeating the computation in Equation (1) for all wind directions and the largest value obtained for all the trusses within that zone are given in Table 2. The load effects considered here are the root bending moment, shear force forestay axial force and backstay axial force, shown in Figure 5.

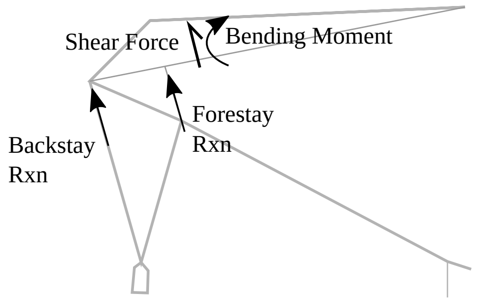

Figure 5. Load effects of interest

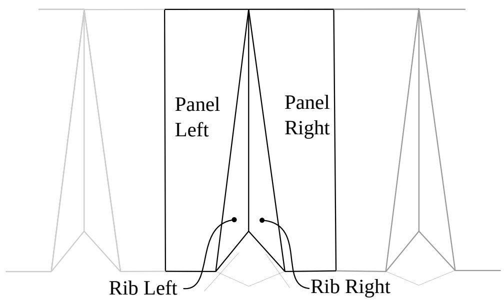

Figure 6. Tributary areas for load effects

The analysis of Trusses 33 to 39 within the zone showed that Truss 33 experienced the largest load effects of interest, and that these load effects occur for different wind directions and at different times**.**

Table 2 gives the C_{pnet} on the tributary areas (shown in Figure 6) generating the peak load effects for trusses 33 to 39. Truss 39 is not critical for any of the load effects shown. The corresponding design (i.e. peak) load effects in non-dimensionalised coefficient form (i.e. the peak values from Equation 4) are defined as $C_{XM} = M/(\frac{1}{2}\rho\bar{U}^2 A_T L_T)$ for bending moments and $C_{XV} = V/(\frac{1}{2}\rho\bar{U}^2 A_T)$ for shear forces. Here, A_T is the tributary area of the truss and L_T is the length of the truss cantilever. Using data in Table D4(A) of AS/NZS1170.2 for the blocked-under case, for a wind direction perpendicular to the free edge of the cantilever, with a K_a = 0.8 gives: design bending moment coefficients of -1.17 and +0.57 and shear force coefficient of -2.19.

Table 2. Cp_{net} distributions for worst-case load effects on tributary supporting Trusses 33-39

Load Effect	Frame No.	Θ (°)	C_{XM} or C_{XV}	Panel Left	Rib Left	Rib Right	Panel Right
BM +ve	34	85	0.4	0.9	0.7	1.1	1.0
BM -ve	33	295	-1.2	-2.9	-2.0	-1.6	-2.7
Shear	33	295	-2.6	-2.9	-2.2	-1.9	-2.6
Forestay (T)	33	295	7.8	-2.9	-2.2	-1.9	-2.6
Forestay (C)	38	30	-3.6	0.3	-0.1	1.7	2.0
Backstay (T)	38	30	2.5	0.3	-0.1	1.7	2.0
Backstay (C)	33	295	-5.2	-2.9	-2.2	-1.9	-2.6

5. Conclusions

A wind tunnel model study was carried out at a model scale of 1/300 to determine design wind loads on the roof of the proposed Stadium. The roof consists of thirty eight panels and triangular ribs that flare out to the back of the stadium. The roof structure comprises columns and "cantilevered" roof trusses that support the panels and ribs.

The outcomes from this study are: the cantilevered flat segments of the roof panels experience large net upwards pressures for winds approaching the inside leading edge. The largest net pressure is at the leading edge on the panels at the NE tail (Panels 32-38). Large net upward pressures are also experienced on the back of the roof for winds approaching from outside the stadium. The area-averaged pressures on the panels are similar to the net pressures on a blocked-under open roof given in AS/NZS1170.2. Shielding from other parts of the stadium and scoreboard result in significantly lower net pressures on the roof on other parts of the stadium. The ribs are subjected to large positive and negative pressures for winds normal to the roof truss span.

Acknowledgements

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