AWESW2022
21st Australasian Wind Engineering Society Workshop
2 – 3 February, 2023

Wind loads on curved free roofs

John Ginger[1], Korah Parackal[1], Simon Ingham[1], Rod Lowe[1] and Christie Hildebrandt[1]

[1]Cyclone Testing Station, James Cook University, Townsville, Australia *john.ginger@jcu.edu.au*

ABSTRACT

This paper presents net wind pressures on a series of curved canopy free roofs obtained by testing three 1/50 scale model configurations in the wind tunnel. Large net negative (outward) and positive (inward) pressures were measured at the leading edges. Increasing positive net pressures were experienced especially on the windward parts of the roof with increasing curvature. Net pressure distributions generating peak horizontal and vertical loads on the frames are used to produce net aerodynamic shape factors $C_{shp,n}$ in a form consistent with AS/NZS 1170.2 (2021).

1. Introduction

Curved, free roofs are built to provide shade and accommodate open recreational spaces. Commonly, metal roof cladding is attached to purlins which are fixed to a curved support frame. The gap between the roof and the ground typically ranges from about 5 to 7m. There is limited wind load data available to enable the cladding and the structural system in these types of roofs be designed satisfactorily. Previous studies by Gumley (1981, 1982), Ginger and Letchford (1992) and Letchford and Ginger (1994) have produced net pressure coefficients, $C_{p,n}$ for flat, mono-slope and pitched canopy roofs for pitch angles of $\alpha = 0^o$, 15^o and 30^o that have been included in AS/NZS1170.2 :2021. This data is based on sparsely populated pressure taps that did not measure local point pressures close to the edges required for designing cladding and the frames close to the ends of the roof.

This paper describes a wind tunnel model study that determined wind pressures on a range of curved, free roofs. The results are also provided in the form of design data consistent with AS/NZS1170.2:2021.

2. Wind tunnel study

The wind tunnel study was carried out in the 2.5m wide × 2m high × 22m long Boundary Layer Wind Tunnel at the Cyclone Testing Station (CTS), James Cook University. The approach Atmospheric Boundary Layer (ABL) was simulated at a length scale L_r of 1/50 over the upstream fetch using a 250 mm high trip board at the upstream end followed by an array of blocks on the tunnel floor. Figure 1 shows the mean velocity and turbulence intensity profiles measured at the working section which satisfactorily matches a suburban terrain category profile in AS/NZS1170.2:2021. The longitudinal length scales of turbulence in this study was estimated to be smaller than the target value by a factor of about 3, which is considered an acceptable degree of relaxation for such a wind tunnel study.

1.1 Roof configurations

Three open (i.e. free), curved roof configurations described in Figure 2 and Table 1 were constructed at a Length scale, L_r of 1/50 and tested in the simulated atmospheric boundary layer flow. The profiles of the roofs were formed by circular arcs.

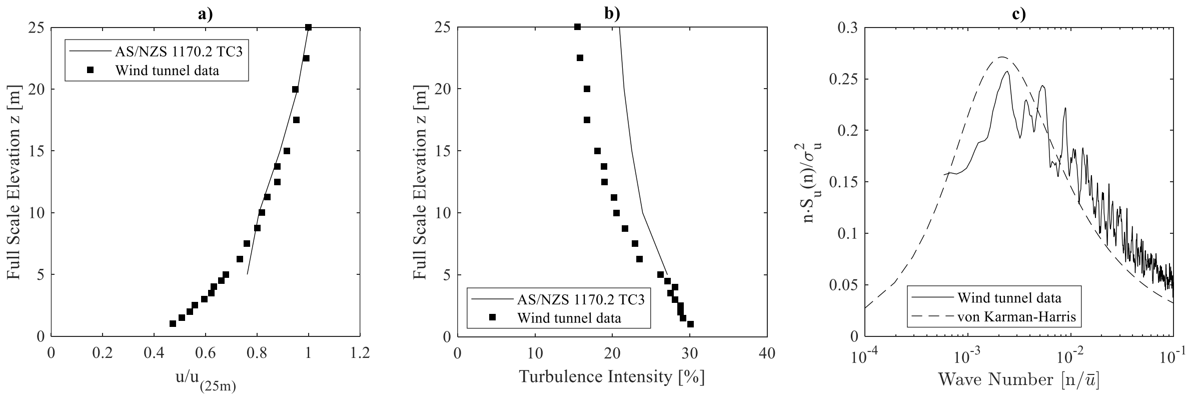


Figure 1. Atmospheric Boundary Layer simulation at a Length Scale of 1/50, a) mean velocity profile, b) turbulence intensity profile and c) power spectral density

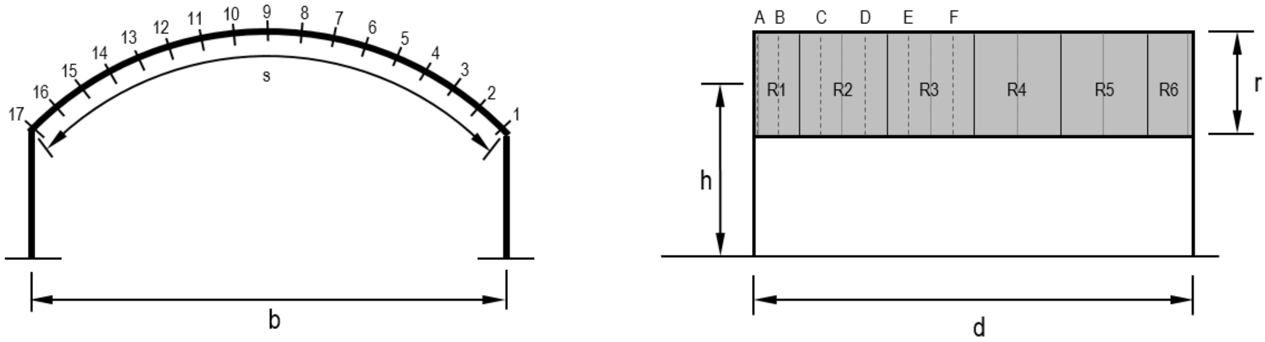


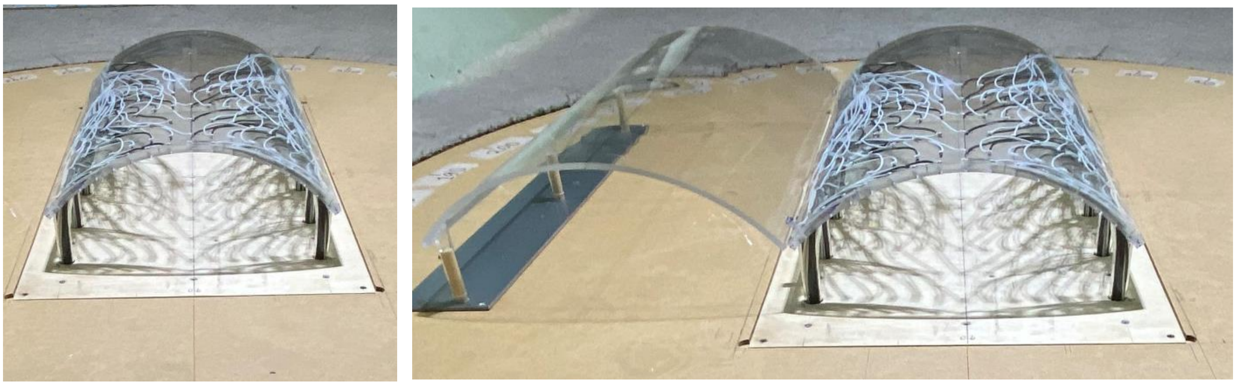
Figure 2. Curved open, (i.e. free) roof building configurations

Table 1. Test Cases – Full scale dimensions

Case #	r (m)	h(m)	b (m)	d (m)	r/b	b/d
1	3.93	5.8	18.3	33.3	0.22	0.55
2	1.83	3.95	20.5	21	0.09	1.0
3	3	5.5	20	40	0.15	0.5

- A Single Span (SS) and a Double Span (DS) are tested for all three Cases specified in Table 1

Pressure taps were installed on the top and bottom surfaces of the roofs on grids A1..17 to F1..17 defined by the location of frames and purlins on the roofs, as shown in Figure 2 for Cases 1, 2 and 3. Pressure taps were connected to pressure transducers in the Turbulent Flow Instrument (TFI) system using 1100mm long × 1.2 mm diameter flexible tubes also enabling simultaneous pressure measurements. The Double Span (DS) cases were tested by installing an identical un-tapped roof on the leeward side of the adjoining Single Span (SS) pressure tapped model, for θ = 0°. Figures 3a and 3b show photographs of the Single Span (SS) and Double Span (DS) models for Case 1 installed in the wind tunnel for testing.



a b

Figure 3. (a) Single Span (SS), (b) Double Span (DS): Case 1

Pressure fluctuations on the top $(p_T(t))$ and bottom, $(p_B(t))$ surface taps were measured for an observation time of 30 seconds at a frequency of 500 Hz and repeated three times for each wind direction from θ = 0° to 355° at 5° intervals. The time (t) varying pressures are represented as pressure coefficients: $C_p(t) = (p(t) - p_o)/\frac{1}{2}\rho\overline{U_h}^2$ referenced to the mean dynamic pressure at mid-roof height, $\frac{1}{2}\rho\overline{U_h}^2$. Here p_0 is the ambient pressure. Net pressure coefficients, $C_{pn}(t) = C_{pT}(t) - C_{pB}(t)$ were also generated for each pressure tap location. The mean, maximum and minimum, pressure coefficients for each 30-second run are given by: $\bar{C}_\mathrm{p} = (\bar{p} - p_o)/\frac{1}{2}\rho\bar{\mathrm{U}}_h^{\,2}$, $\hat{C}_p = (\hat{p} - p_o)\,/\frac{1}{2}\rho\bar{\mathrm{U}}_h^{\,2}$ and $\check{C}_p = \widetilde{(p - p_o)}/\frac{1}{2}\rho\bar{\mathrm{U}}_h^{\,2}$, where, $\bar{p}$, $\hat{p}$ and $\check{p}$ are the mean, maximum and minimum pressures in each 30 s time period $\overline{U}_h$ is the mean wind speed at mid roof-height (h) and ρ is the density of air. The data presented here are based on the average values obtained from the three repeat runs for each approach wind direction.

Design pressures can be derived from this wind tunnel test data using the peak pressure coefficient C_{peak} (i.e. the maximum or minimum pressure coefficient ($\hat{C}_p, \check{C}_p$)), and $\overline{U}_h$ the equivalent 10-minute mean wind speed at the reference height h, and related to the aerodynamic shape factors C_{shp} in AS/NZS 1170.2 (2021). Here, $C_{shp} = \left(\overline{U}_h^2/\widehat{U}_h^2\right)C_{peak} = C_{peak}/G_u^2$, where, $G_u = \widehat{U}_h/\overline{U}_h$ is the velocity gust factor at the height *h.*

3. Analysis and results: Single Span (SS) roof – Net pressures

The net aerodynamic shape factors, $C_{shp,n}$ for cladding design for winds approaching from θ = 0° ± 45° and 90° ± 40° for Case 1 are given in Figure 4 and Figure 5, respectively. Figures 4a-b for θ = 0° ± 45° show that the windward part of the roof (Taps 1-6) experiences positive net pressure coefficients. The central part of the roof (Taps 7-11), and the leeward part of the roof (Taps 12-17) experience negative net pressure coefficients. Figures 5a-b for θ = 90° ± 40° show that the region near the windward edge of the roof (Grids A-B) experience large positive and negative net pressure coefficients, which accounts for application of local pressure factors K_L > 1.0 as noted in AS/NZS 1170.2:2021. The net positive pressures tend to increase as the curvature of the roof increases from Case 2 to 3 to 1. The net negative pressures tend to increase in magnitude as the curvature of the roof decreases from Case 1 to 3 to 2.

a) Maximum

	A	B	C	D	E	F
1	2.08	1.68	2.24	1.75	2.18	1.50
2	2.48	1.54	1.55	1.26	1.20	1.16
3	1.68	1.33	1.29	0.99	0.87	0.90
4	1.71	1.33	1.12	0.80	0.66	0.60
5	2.16	1.33	0.68	0.51	0.43	0.43
6	1.96	1.30	0.48	0.27	0.26	0.24
7	2.42	1.26	0.41	0.24	0.10	0.05
8	2.04	1.22	0.21	0.17	0.04	0.01
9	1.99	1.40	0.51	0.12	-0.04	-0.04
10	1.52	1.66	0.36	0.03	-0.06	0.05
11	1.04	0.83	0.36	0.04	-0.06	-0.02
12	0.82	0.48	0.41	0.12	-0.02	-0.07
13	0.77	0.55	0.21	0.05	0.06	0.09
14	0.63	0.45	0.34	0.26	0.23	0.19
15	0.54	0.47	0.37	0.32	0.40	0.24
16	0.86	0.45	0.44	0.31	0.30	0.26
17	0.61	0.40	0.53	0.31	0.40	0.29

b) Minimum

	A	B	C	D	E	F
1	-0.68	-0.59	-0.37	-0.50	-0.44	-0.48
2	-0.69	-0.29	-0.39	-0.27	-0.32	-0.33
3	-0.86	-0.38	-0.33	-0.42	-0.41	-0.42
4	-1.20	-0.38	-0.52	-0.46	-0.50	-0.62
5	-1.56	-0.49	-0.57	-0.58	-0.67	-0.70
6	-1.68	-0.66	-0.85	-0.73	-0.84	-0.85
7	-1.99	-0.78	-0.98	-0.98	-0.90	-1.05
8	-2.55	-0.92	-1.16	-1.03	-0.89	-0.91
9	-2.88	-1.09	-1.24	-1.17	-1.03	-0.97
10	-2.97	-1.41	-1.37	-1.25	-1.14	-1.08
11	-3.26	-1.93	-1.35	-1.36	-1.19	-1.13
12	-3.59	-1.77	-1.35	-1.31	-1.13	-1.13
13	-3.31	-2.00	-1.36	-1.24	-1.12	-1.10
14	-2.46	-2.02	-1.36	-1.18	-1.03	-1.04
15	-2.04	-1.99	-1.36	-1.06	-0.90	-0.81
16	-1.79	-1.84	-1.47	-1.06	-0.89	-0.74
17	-1.54	-1.41	-1.12	-0.90	-0.68	-0.64

Figure 4. Net aerodynamic shape factors $C_{shp,n}$, θ = 0° ± 45° Single Span (SS), Case 1:

a) Maximum

	A	B	C	D	E	F
1	1.88	1.64	1.68	1.15	1.04	0.85
2	3.65	1.69	1.42	1.05	0.80	0.72
3	3.40	1.41	1.17	0.90	0.64	0.58
4	2.46	1.33	0.94	0.75	0.54	0.43
5	2.37	1.71	0.77	0.42	0.35	0.33
6	2.11	1.65	0.61	0.25	0.14	0.21
7	2.38	1.81	0.69	0.28	0.14	0.13
8	2.41	1.66	0.63	0.35	0.22	0.16
9	2.47	1.75	0.71	0.34	0.17	0.14
10	2.53	2.00	0.69	0.38	0.16	0.14
11	2.32	1.66	0.61	0.36	0.21	0.16
12	2.48	1.60	0.65	0.32	0.23	0.15
13	2.57	1.43	0.66	0.29	0.30	0.23
14	2.52	1.35	0.77	0.50	0.45	0.35
15	3.96	1.50	0.89	0.76	0.59	0.51
16	2.69	1.54	1.17	0.86	0.72	0.67
17	2.01	1.50	1.69	0.91	0.98	0.78

b) Minimum

	A	B	C	D	E	F
1	-2.65	-1.22	-0.91	-0.71	-0.66	-0.59
2	-2.36	-1.43	-1.39	-0.71	-0.89	-0.52
3	-2.17	-1.65	-1.12	-0.83	-0.76	-0.55
4	-2.35	-1.67	-1.03	-0.89	-0.70	-0.68
5	-2.82	-1.62	-0.93	-0.93	-0.78	-0.68
6	-2.98	-1.74	-0.94	-0.85	-0.82	-0.72
7	-2.97	-1.59	-0.95	-0.89	-0.78	-1.00
8	-2.72	-1.76	-1.06	-0.91	-0.81	-0.77
9	-2.59	-1.22	-1.07	-0.94	-0.95	-0.86
10	-2.95	-1.54	-1.03	-1.02	-0.97	-0.94
11	-3.30	-1.48	-1.02	-1.11	-0.95	-0.96
12	-3.25	-1.72	-0.97	-0.97	-0.95	-0.91
13	-2.58	-1.75	-1.02	-1.03	-0.95	-0.87
14	-2.55	-1.90	-1.06	-0.87	-0.89	-0.75
15	-2.30	-1.83	-1.21	-0.80	-0.79	-0.64
16	-2.27	-1.46	-1.40	-0.82	-0.76	-0.51
17	-2.82	-1.26	-1.04	-0.73	-0.59	-0.41

Figure 5. Net aerodynamic shape factors $C_{shp,n}$, θ = 90° ± 40° Single Span (SS), Case 1:

Net "area-averaged" pressures on Patches 1..17 on the roof tributary areas R1, R2 and R3 are used to obtain the structural loads, The time-varying loads acting on each patch are used to obtain load effects ($X(t)$) on each tributary area, in coefficient form C_x given by Equation 1.

$$C_X(t) = \frac{X(t)}{\frac{1}{2}\rho \bar{U}_h^2 . A_N}; \quad X(t) = \left(\sum_{i=1}^{N} \beta_i \, A_i C_{pn_i}(t)\right) \times {}^1\!/_2\, \rho \bar{U}_h^2 \qquad (1)$$

Here, β_i is the influence coefficient for the load applied at patch, *i*, A_i is the area for patch *i*, $C_{pn_i}(t)$ is the net pressure coefficient on patch, *i* at time *t*, *N* is the Number of patches on the tributary area influencing the load effect, *X*, A_N is the total area comprising the area of all patches within the tributary.

Directions of Horizontal Force (H) and Vertical Force (V) are defined in Figure 6. Additionally, roof zones for the application of C_{pn} corresponding to the worst case load effects are also shown in Figure 6.

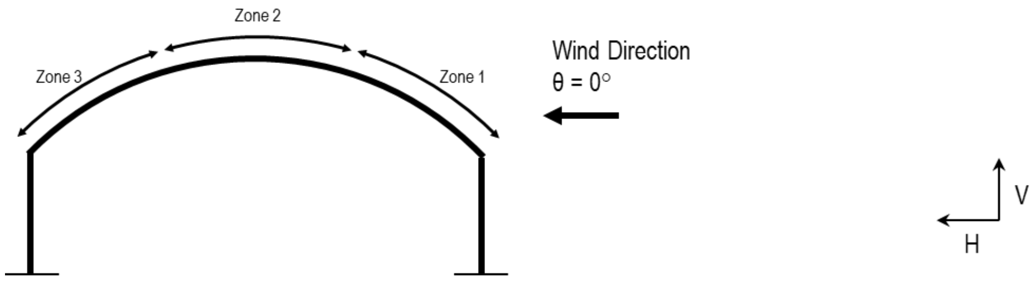


Figure 6. Roof zones with respect to wind direction and; Horizontal (H) and vertical (V) loads on the frames

The variation of peak (maximum and minimum) horizontal, H and vertical, V, load coefficients on tributary areas R1 and R2 with the approach wind direction for the single-span (SS) Case 1, are shown in Figures 7 and 8 respectively. These figures show that R1 at the windward end of the roof experiences the largest horizontal loads, C_H for wind directions of about θ = 45° and 135°. R1 also experiences the largest upwards and downwards vertical loads, C_V for θ = 45° to 135°. R2 experiences horizontal and vertical loads that are about 40 to 50 % lower. The addition of a span does not impose additional loads.

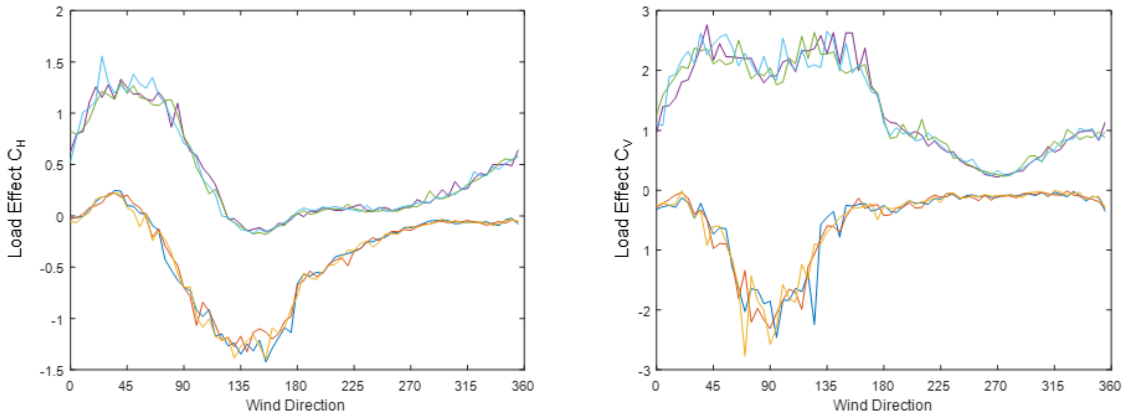


Figure 7. Case 1 Single Span (SS) – Tributary R1: maximum and minimum load effects; *left:* (C_H); *right:* (C_V)

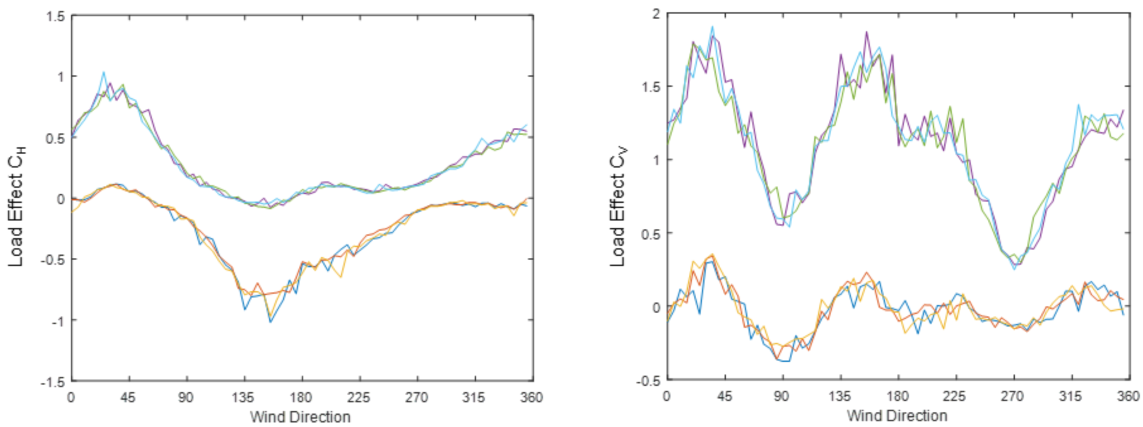


Figure 8. Case 1 Single Span (SS) – Tributary R2: maximum and minimum load effects; *left:* (C_H); *right:* (C_V)

The quasi static net pressure distributions, C_{pn} for inclusion in AS/NZS1170.2 for Case 1 for θ = 0° and θ = 90° are given in Figure 9.

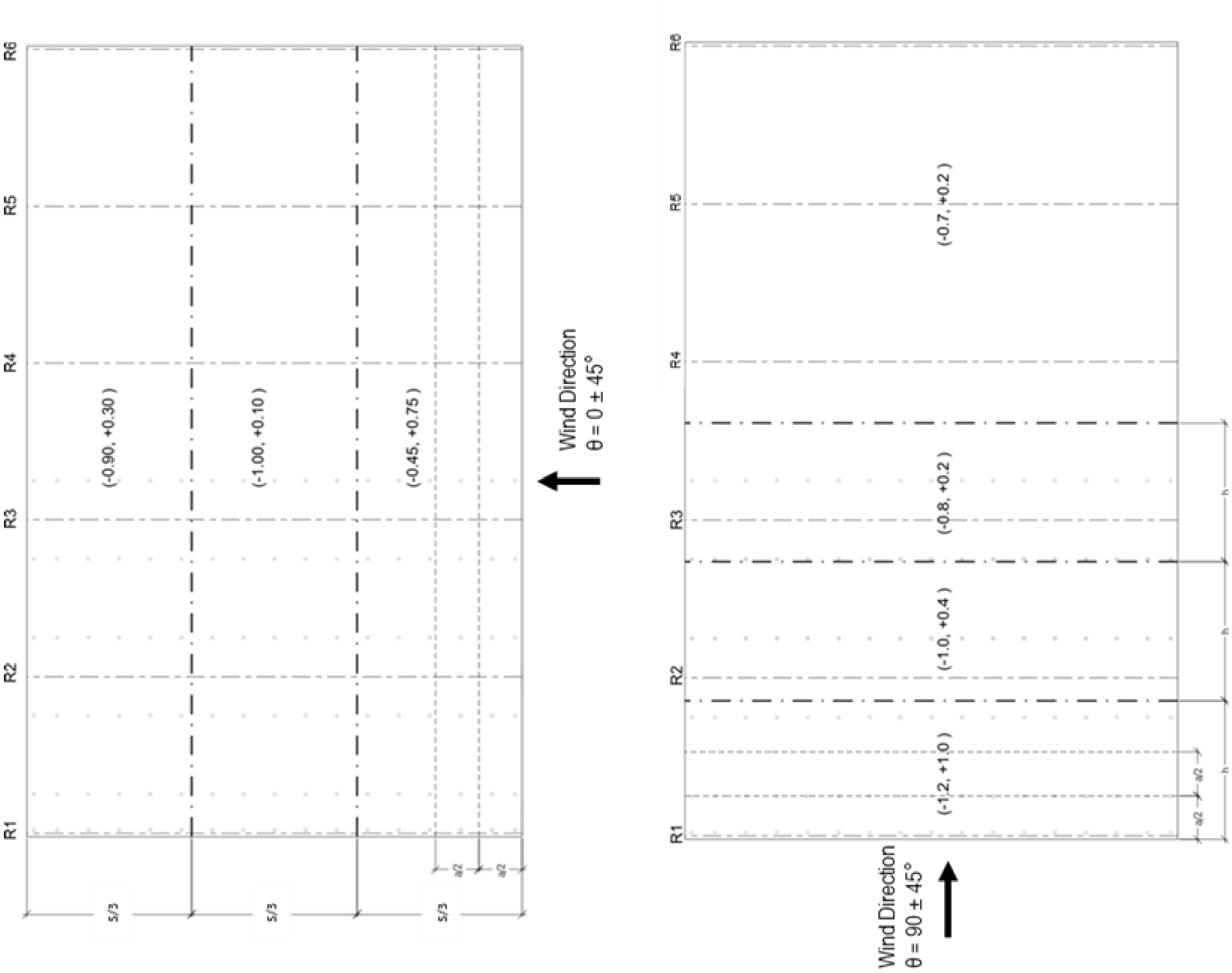


Figure 9. C_{pn} for inclusion in AS/NZS1170.2 for θ = 0° and θ = 90° ; Case 1

4. Conclusions

The results show that: Large net negative (outward) pressures net positive (inward) were measured at the ends of the roof for oblique approach winds. The net pressures coefficients, $\widetilde{C_{p,n}}$, to be applied with the relevant area reduction factor K_a and local pressure factor K_l as in AS/NZS1170.2:2021 for the design of cladding and major structural elements are provided. Increasing curvature of the roof increases horizontal loads decreases vertical loads.

References

Gumley, S. J., (1981), “Panel loading mean pressure study for canopy roofs” Uni of Qxford, Dept of Engineering Science, OUEL Report No. 1380/81

Gumley, S. J., (1982), “Design extreme pressures - A parametric study for canopy roofs” Uni of Qxford, Dept of Engineering Science, OUEL Report No. 1394/82.

Standards Australia (2021), *Structural design actions. Part 2: wind actions*, Australian/New Zealand Standard, AS/NZS 1170.2:2021, Standards Australia, Sydney, New South Wales, Australia.

Letchford C. W. and Ginger J. D., *Wind loads on planar canopy roofs, Part 1: mean pressure distributions*, Journal of Wind Engineering and Industrial Aerodynamics Vol 45, 1992, pp 25-45.

Ginger J. D. and Letchford C. W., *Wind loads on planar canopy roofs, Part 2: fluctuating pressure distributions and correlations,* Journal of Wind Engineering and Industrial Aerodynamics Vol51, pp 353 – 370, 1994.