Net Pressures and Net Pressure Factors for Building Roof Cladding Elements

G.G. Bodhinayake[1], J.D. Ginger[2] and D.J. Henderson[3]
[1,2,3]*College of Science and Engineering, James Cook University, Townsville, Queensland, 4811, Australia.*
[1]*geeth.bodhinayake@my.jcu.edu.au*, [2]*john.ginger@jcu.edu.au*, [3]*david.henderson@jcu.edu.au.*

ABSTRACT

The combination of internal and external pressures generate net wind pressures on the building elements. The net pressure factor depends on the peak net, peak external and peak internal pressures acting on the cladding element. The net pressures on roof cladding obtained from a 1:200 scale model study showed that net pressures are large at the leading windward roof edge. The net pressure factor (F_{C2}), the ratio between minimum net pressure and the difference between minimum external and maximum internal pressures are calculated for different roof cladding locations. The largest net pressure factor is obtained for the windward roof corner. The wind direction for the largest net pressure factor and the highest net pressure is not always the same. The net pressure factor for the windward corner (Zone #1) of nominally sealed building and building with a large opening are around 0.95 and 0.90, respectively. The area-averaged net pressure factors are higher than net pressure factors for point pressures but are within $\pm$5%.

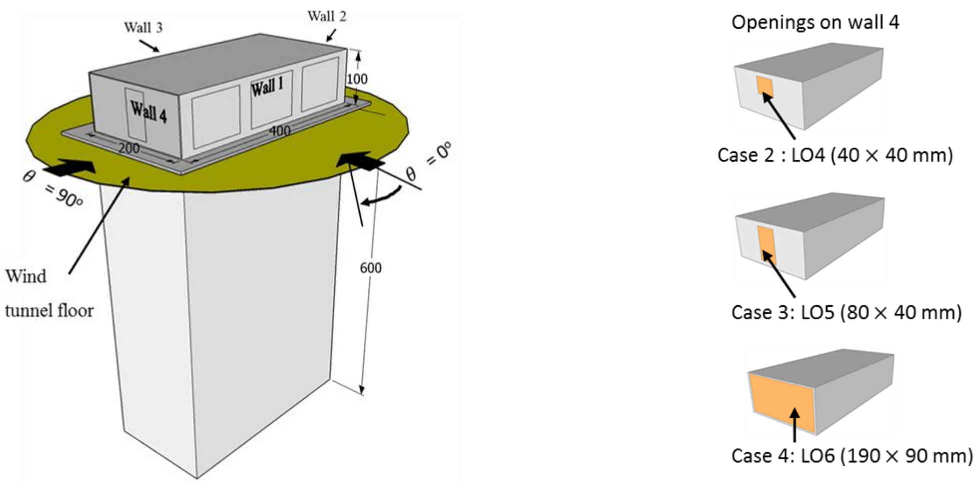
1. Introduction

The approach wind flow generates spatially and temporally varying external pressures around the building envelope. These external pressures are positive on the windward wall and negative on sidewalls, leeward wall, and roof. The pressure around the envelope influences the internal pressure, which depends on the airflow in and out of the openings in the building envelope. Internal pressure fluctuations are small in the nominally sealed buildings and large in a building with a large opening. Large net pressures generated by the combination of internal and external pressures may lead to failures of the cladding on a building. Generally, damage is caused by the internal pressurisation of a building when the opening is on the windward wall. In windstorms, these large positive internal pressures can also cause catastrophic failures of the structural system of industrial buildings.

Bodhinayake (2020) studied the net pressure fluctuations on the roof and wall cladding of the industrial buildings in his PhD thesis, and this paper represents a summary from his PhD thesis. Ginger et al. (1997) analysed the net pressure fluctuations on the WERFL test building by combining external and internal pressure time histories. Compared to the nominally sealed building, when the building has an opening on the windward wall, they found that net positive loads on the windward wall were decreased and net suction loads on the roof, side walls, and leeward walls increased due to large positive internal pressure fluctuations. Combinations of peak external and peak internal pressure have been studied by Xu and Lou (2017), defined the combination factors as the ratio between maximum or minimum external pressure magnitude (or internal) and maximum or minimum net pressure magnitude (i.e., combination factor for external $= C_{\hat{p}e}/C_{\hat{p},net}$). Accordingly, they introduced a combination factor of 0.98 for peak internal pressures and a combination factor of 0.43 for external pressure. Combination factors for internal and external pressure are almost equal to 1 for wall maximum net pressures, showing the equivalent maximum pressures in net, external and internal pressures. Wind loading standard AS/NZS 1170.2, 2011 provides combination factors, K_C, which account for the lack of correlation between internal and external pressures. AS/NZS 1170.2 specifies that K_C = 1 for net cladding loads when $|C_{pi}|$ < 0.2, which accounts for the minor contribution of the internal pressure (i.e., Case #2). For other instances, K_C = 0.9 for deriving net cladding loads, when pressures act on two effective surfaces.

2. Wind Tunnel Experiment

A wind tunnel test was carried out in the wind tunnel at the Cyclone Testing Station, James Cook University, in an approach terrain category 2 as defined by AS/NZS 1170.2,2011. Figure 1(a) shows 3D view of the 1:200 scale-building model with the dimensions of 400 mm × 200 mm × 100 mm. The internal volume was distorted by an additional depth of 600 mm under the turntable of the wind tunnel as explained by Holmes (1979). In addition, total porous area to wall area ratio was maintained uniformly for nominally sealed building (Case #1) by evenly-distributed, 3 mm and 1.5 mm diameter porous holes along the four walls to achieve the maximum of 0.6% porosity level on each wall. Figure 1(b) shows the three large wall opening, Cases #2, 3 and 4 (LO4, LO5, and LO6) on Wall #4 of 40 mm × 40 mm, 80 mm × 40 mm and 190 mm × 90 mm respectively.



(a) 3D view of the model with volume distortion (b) Three opening sizes on Wall 4

Figure 1. 1:200 scale wind-tunnel model

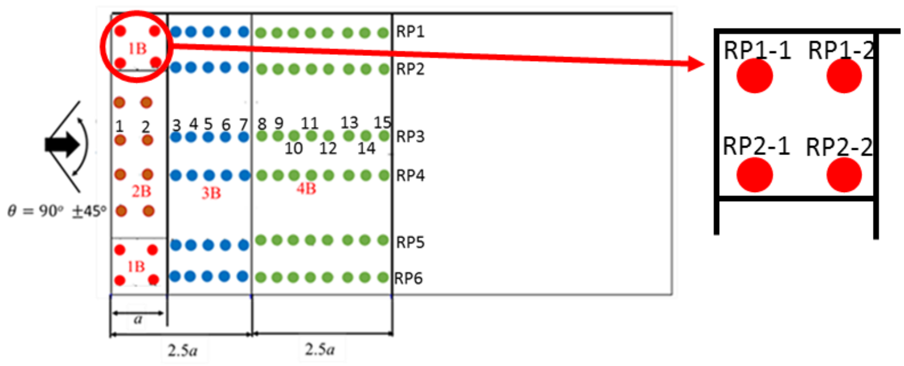


Figure 2. Pressure taps on roof Zones 1B, 2B, 3B and 4B for wind flows 90° ± 45°

The measured mean wind speed at the roof height ($\overline{U}_h$) is about 11 m/s, and turbulence intensity (I_u) at roof height is 0.18. Tests were carried out for a range of wind directions, θ = 90° to 360° in 10° intervals for 16 s at a frequency of 625 Hz. Tests were repeated five times for each wind directions, and Wall 4 was the windward wall for all tests configurations at θ =90°. Figure 2 shows the roof zones considered for point pressures and area-averaged pressures by averaging the pressures of 4, 8, 30, and 42 pressure taps on roof Zones #1B, 2B, 3B, and 4B, respectively. The time (t) varying external pressure, $(p_e(t))$ and internal pressure, $(p_i(t))$ were converted into pressure coefficients $(C_p(t))$ to give mean, standard deviation, maximum and minimum coefficients as defined; $C_{\bar{p}} = \frac{\bar{p}}{(1/2)\,\rho_a \bar{U}_h^2}$, $C_{\sigma p} = \frac{\sigma_p}{(1/2)\,\rho_a \bar{U}_h^2}$, $C_{\hat{p}} = \frac{\hat{p}}{(1/2)\,\rho_a \bar{U}_h^2}$, $C_{\check{p}} = \frac{\check{p}}{(1/2)\,\rho_a \bar{U}_h^2}$; where, $\bar{p}$, $\sigma_p, \hat{p}$ and $\check{p}$ are the mean, standard deviation, maximum and minimum pressures ; $\bar{U}_h$ is the mean wind speed at the roof height (h = 100 mm) and ρ_a is the density of air.

3. Net pressures and net pressure factors

External and internal pressure time histories were recorded for five repeat runs for each wind direction, and the time-varying net pressure coefficients, $C_{pnet}(t)$ (as defined in Equation 1) were generated for each pressure tap. The mean, standard deviation, and peak (maximum and minimum) external, internal and net pressure coefficients are obtained by taking the average values from five repeat runs each of 16 s duration.

$$C_{p,net}(t) = C_{pe}(t) \; - C_{pi}(t) \tag{1}$$

The peak net pressure coefficients in magnitude are less than the difference between peak external and peak internal pressures (i.e., $|C_{\check{p},net}| < |C_{\check{p}e} - C_{\hat{p}i}|$), since the peak external and peak internal pressures do not coincide in time. Accordingly, net pressure factor, F_{C2} is determined for the outward net pressures acting on the building envelope for each θ in Equations 2. The net pressure factor for each roof zone is selected based on the critical wind direction, which produces the highest peak net pressures, and F_{C2} values are compared with the combination factor K_C given in the wind-loading standard AS/NZS 1170.2 (2011).

$$F_{C2}(\theta) = \frac{C_{\check{p},net}(\theta)}{C_{\check{p}e}(\theta) - C_{\hat{p}i}(\theta)} \tag{2}$$

4. Results and discussion

4.1 Nominally sealed building (Case #1)

Figures 3(a) shows the minimum net point pressures (i.e., considering a single tap in Zone #1B) and area-averaged pressures for Zone #1B of the nominally sealed building for wind directions 90° to 135°. High negative net pressures occurred at RP1-1 for wind directions 110° to 125°. The area-averaged minimum net pressures vary around -3.0, lower than the point pressures in the zone due to the spatial filtering. The area-averaged minimum net pressures decrease towards the middle of the roof as shown by the reduction in the minimum pressures proposed from Zones #1B, 2B, 3B and 4B in Figure 3(b). The area-averaged $C_{\check{p},net}$ of -3.0 (θ = 110°), -2.8 (θ = 120°), -1.3 (θ = 90°), and -1.0 (θ = 135°) are obtained for roof Zones #1B, 2B, 3B and 4B, respectively.

Figure 4(a) shows the net pressure factors calculated based on point pressures on RP1-1, RP2-8, RP3-2, RP4-3, and RP5-12 represent the four roof zones of the nominally sealed building. F_{C2} decreases towards the middle of the roof from windward roof edge of the building. Figure 4(b) shows the area-averaged net pressure factors determined using the area-averaged minimum and maximum pressures for the roof zones of the nominally sealed building for wind directions 90° to 135°. The largest suction net pressure and largest net pressure factor do not occur at the same wind direction in both point pressures and area-averaged pressures. Thus, net pressure factor related to the largest suction net pressure is selected as a particular net pressure factor for roof zone for further comparison.

Accordingly, area-averaged F_{C2}s are 0.95, 0.90, 0.85, and 0.85 for Zones #1B, 2B, 3B, and 4B, respectively, which is approximately 5% less for some roof areas than the net pressure factors calculated at the point pressures for each roof zone. This is because the spatial filtering on area-averaged net pressures has a greater reduction than area-averaged external pressures with less effect from internal pressure fluctuations.

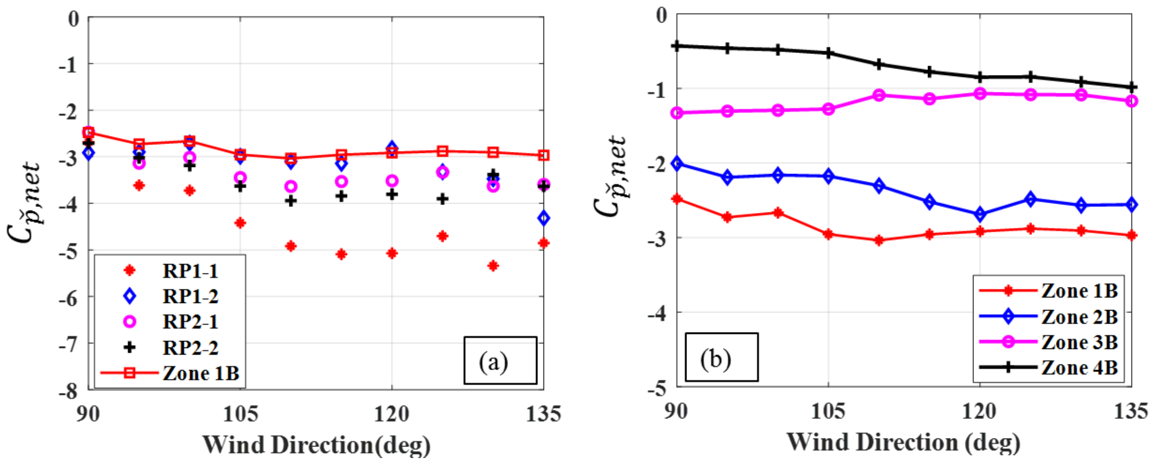


Figure 3. (a) Minimum p*oint and area-averaged net pressures for Zone #1B (b) Area-averaged* $C_{\breve{p},net}$ *for roof Zones #1B,2B,3B and 4B of the nominally sealed building (Case #1) for θ = 90°-135°*

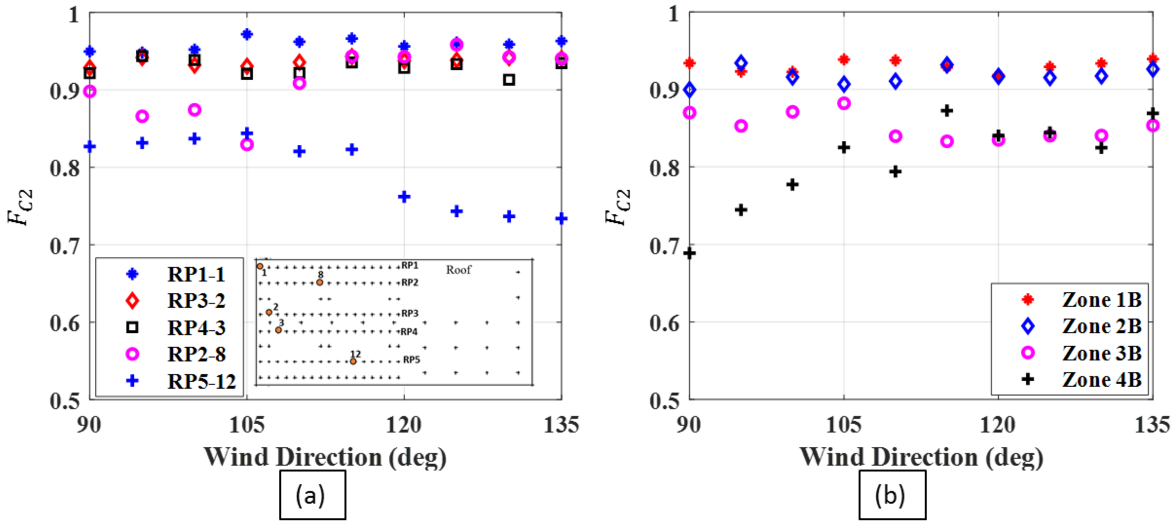


Figure 4. N*et pressure factors,* F_{C2} *for θ= 90° to 135°, nominally sealed building (a) point pressures* to represent 4 zones (b) *Area-averaged roof zones*

4.2 Building with a large opening (Case 4)

Figure 5(a) shows minimum net pressure coefficients of single pressure taps and area-averaged net pressures for Zone #1B for the building with a large opening (Case #04) for θ = 90°-135°. Large $C_{\breve{p},net}$s are obtained at RP1-1 and RP2-1 for critical wind directions. The area-averaged $C_{\breve{p},net}$ varies around -4.5, which is 40% less than the largest minimum net pressure at RP1-1 for θ = 110°. This is due to the spatial filtering of four pressure taps when producing the area-averaged net pressure fluctuations. Figure 5(b) shows the minimum area-averaged net pressures on Zones #1B, 2B, 3B, and 4B of the building with a large opening (Case #04) for θ = 90°-135°. Figure 5(b) further shows that $C_{\breve{p},net}$ decreases towards the middle of the roof due to spatial filtering of 30 and 42 pressure taps of the area-averaged pressures. Zone #1B experiences the largest area-averaged $C_{\breve{p},net}$ of -5.0 at θ = 105°, while -4.5 at θ = 130° for Zone #2B, -3.0 and -2.0 at θ = 90° for Zone #3B and #4B, respectively.

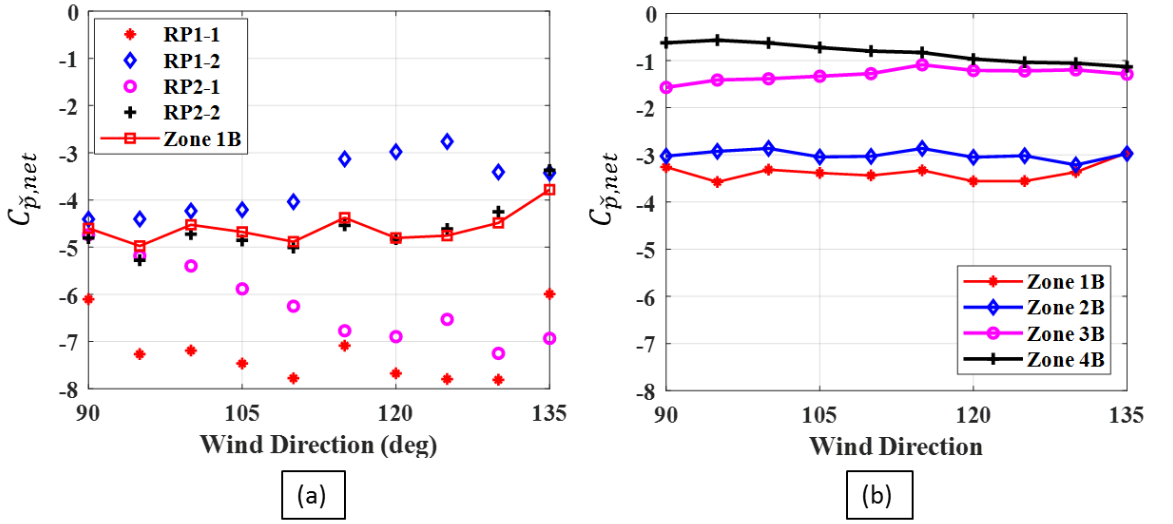


Figure 5. (a) Minimum p*oint net pressures area-averaged* $C_{\breve{p},net}$ *for Zone #1B (b) Area-averaged* $C_{\breve{p},net}$*for roof Zones 1B,2B,3B and 4B of the building with a large opening(Case #4) for θ = 90°-135°*

Figure 6(a) shows the net pressure factors, F_{C2} for Case #04 when the opening is on the windward end wall for wind directions 90° to 135°. The F_{C2} values depend on wind direction and location of the tap and F_{C2} varies between 0.55 to 0.95. The net pressure factors for the roof corner tap (RP1-1) range between 0.9 to 0.95. Figure 6(b) shows the calculated net pressure factors for different roof zones for Case #4 based on the area-averaged external, net, and internal pressures. The area-averaged net pressure factors for each roof zone are defined considering the wind direction of the highest suction net pressures on a particular roof zone. Accordingly, the largest F_{C2} for Zone #1B is 0.9 at θ = 95°, which produces the highest net negative pressure, as shown in Figure 5(a). Similarly, the area-averaged net pressure factors for Zone #2B of 0.95 (θ = 130°), for Zones #3B and #4B at 90° are about 0.90 and 0.85. The calculated net pressure factors based on the point pressures are within $\pm$5% of the area-averaged net pressure factors. The spatial filtering reduces the high external and net peaks, so the area-averaged net pressure factor may not represent the actual reduction to the peak net pressures in the cladding design. Therefore, the net pressure factors based on point pressures are more appropriate for cladding design.

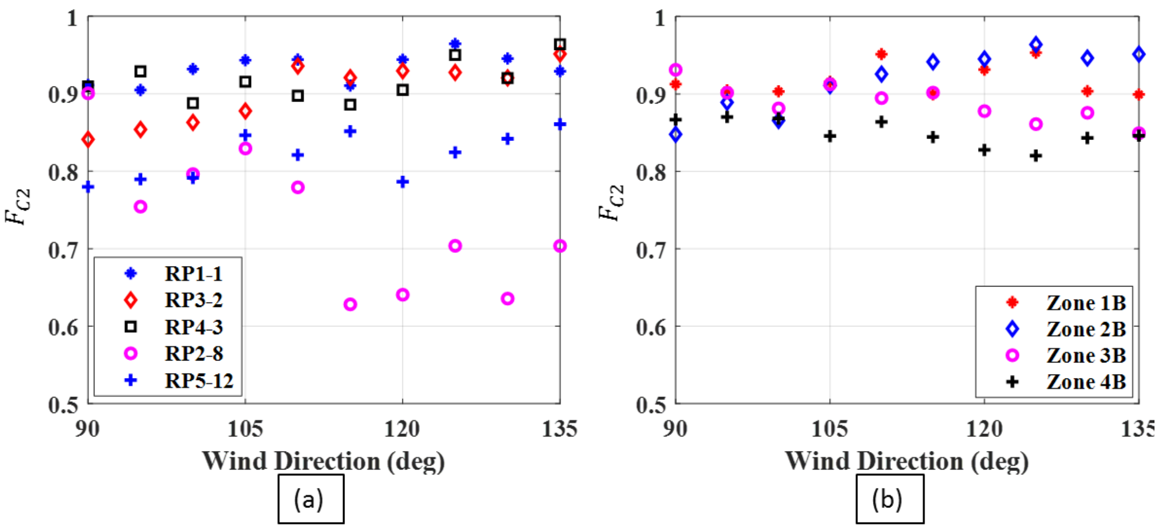


Figure 6. (a) N*et pressure factors calculated at the point pressures* to represent 4 zones (b) *Area-averaged net pressure factors* (F_{C2}) *for roof zones for building with a large opening (Case #4), θ= 90° to 135°*

Table 1 shows net pressure factors at different roof Zones #1B, 2B, 3B, and 4B based on point pressures and area-averaged pressures for different opening configurations. Most of the area-averaged net pressure factors are higher than net pressure factors for point pressures but are within $\pm$5%. This is due to the similar peak internal pressure for both net pressure factors (based on point pressures and area-averaged pressures), but the difference between area-averaged peak external and peak internal pressures are smaller than the difference between point peak pressures. The area-averaged F_{C2} values do not show trends or pattern. However, area-averaged F_{C2} values can be summarised as 0.95 for Zone #1B, 0.9 for Zone #2B and #3B and 0.85 for Zone #4B, which is 5% higher for Zone #1B and 5% less for other roof Zones compared to the combination factor (K_C = 0.9) defined in AS/NZS 1170.2, 2011.

Table 1. *Net pressure factors for different roof Zones #1B, 2B, 3B, and 4B based on point pressures and area-averaged pressures*

Case #	F_{C2} based on point pressures				F_{C2} based on area-averaged pressures			
	Zone #1B	Zone #2B	Zone #3B	Zone #4B	Zone #1B	Zone #2B	Zone #3B	Zone #4B
2	0.91	0.88	0.87	0.79	0.94	0.94	0.93	0.84
3	0.91	0.78	0.92	0.77	0.93	0.90	0.86	0.82
4	0.92	0.95	0.93	0.81	0.90	0.95	0.90	0.85

5. Conclusions

- The highest net pressure coefficient is critical for design, therefore F_{C2} is derived for the wind direction that produces the largest peak net pressures of the particular cladding location.
- The area-averaged $C_{\breve{p},net}$ decreases for all the roof zones due to the spatial filtering of area-averaged pressures. The area-averaged effect is increased toward the middle of the roof since the higher number of pressure taps are considered the larger area on the roof, Zones #3B and #4B.
- For Nominally sealed building, the net pressure reduction factors, F_{C2} for windward roof corner (Zone #1B) is about 0.95, windward edge (Zone #2B) is about 0.90, and reattachment area and middle of the roof (Zone #3B and #4B) is about 0.85. F_{C2}s are 5% to 10% lower compared with K_C =1 in the AS/NZS 1170.2 (2011).
- For building with a large opening, the net pressure factors for Zone #1B, #2B, #3B and #4B are calculated as about 0.95, 0.95, 0.90 and 0.85, respectively, which are 5% higher on the roof corner, and 10% lower on the middle of the roof compared with K_C =0.9 in the AS/NZS 1170.2 (2011).

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