The effect of sunshading elements on cladding pressures

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ABSTRACT: The results of a detailed study into the effect of sunshading devices on the cladding pressure distribution on a tall building are presented. The study is based on an average-sized tall building and investigates the effect of the 11 most commonly used combinations of three basic sunshading elements. Generally, the sunshading elements tended to reduce the pressures on the side walls, which are most critical in terms of cladding design while the windward wall pressures were increased. However, different combinations of sunshading elements had different effects on the cladding pressure distributions. This paper recommends the incorporation of guidelines regarding the effect of these appurtenances in wind loading codes.

1 INRODUCTION

With the increasing awareness of the importance of energy efficient design in buildings, the use of sunshading elements for solar energy control, particularly in office buildings, is becoming an increasingly attractive option. The aim of this work is to present a method of predicting the design wind loads for the design of cladding on buildings that incorporate sunshading elements such as mullions, concrete eyebrows and sun shields. Despite the importance of this subject with regard to the rational design of cladding, particularly glass cladding, the amount of work done on this subject is very limited. In addition to the work published by Newberry & Eaton (1974), some work was done on the effect of external mullions by Leadon & Kownacki (1979) and more recent work was presented by Stathopoulos & Zhu (1988). Comparisons were made with findings by these authors whenever possible.

A series of wind tunnel tests was carried based on a 12-storey prototype building, which represents an average-sized tall building. A number of configurations and combinations of sunshading elements were investigated for their effects on the wind pressure distribution across the building facade. The results were analysed in order to arrive at a set of generalised parameters for the design of cladding on buildings that incorporate such elements. The variations were related to the type of configuration of sunshading elements, the side ratio (d/b), the face of the building with respect to the wind direction and the position on the face.

2 EXPERIMENTAL SETUP

2.1 *Model*

A model, representing a building that is 45m in height, having an aspect ratio (h/b) of 3 and a side ratio (d/b) of 2 was used for this investigation. A geometric scale of 1:100 allows a close simulation of the sunshading elements. The result of the investigation by Stathopoulos & Zhu (1988) was based on a model having a geometric scale of 1:400, which caused them to use oversized appurtenances. Hence it may be difficult to directly compare results. The model was made from perspex and had a smooth finish. Eleven configurations of sunshading elements were investigated. These are derived from the three basic elements, described in Figure 1. The selection of the various configurations of sunshading elements is based on the current techniques employed by architects for solar energy control and for protection from solar radiation and glare. Table 1 describes the combination of the basic sunshading elements used in each configuration.

All strips used in modeling the projecting vertical and horizontal elements are made from soldered sheet metal of 0.4mm in thickness (40mm in full scale) and in 10mm depth (1.0m in full scale). The various configurations were attached to the base model using double-sided tape.

Configuration A and C are of vertical projections such as mullions or fins. They are spaced at 5.0m centres and 1.7m centres in configurations A and C, respectively.

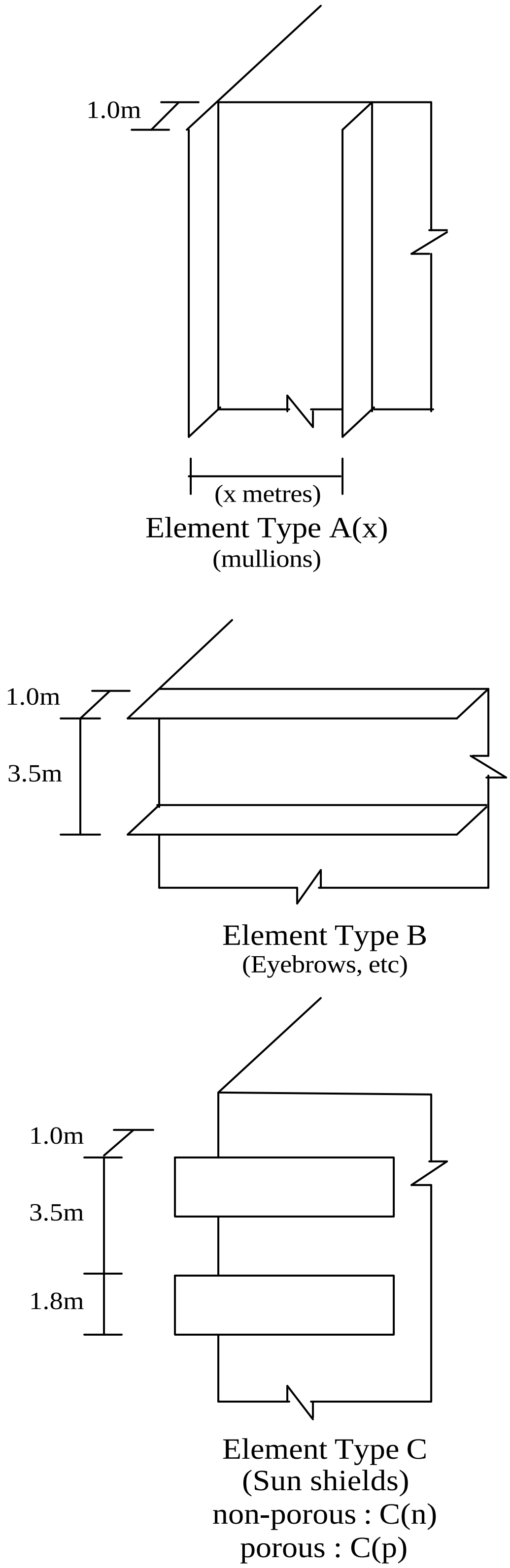

Figure 1. The three basic sunshading elements: A, B and C.

Configuration B represents horizontal projections such as long, narrow open balconies, horizontal fins or concrete eyebrows separated by a floor height of 3.5m.

Configurations H and I have sun shields attached to the horizontal projections, being 1.8m high and the centres level with the floor levels. These sun shields are solid in configuration H are made from brass mesh (24 wires per inch) in configuration I. The ratio of void to solid surface of the brass mesh is roughly 1:1. These represent balconies or "eyebrows" with solid or porous overhangs (or louvres) with the overhangs serving as sunshading elements.

Configurations E, F and G involve a combination of vertical and horizontal projections. These vary in terms of the spacing of the vertical projections. The spacing of the vertical projections is the whole building width, 5m and 1.7m for configurations E, F and G, respectively.

Configuration D is a combination of vertical projections at 1.7m spacing (as in configuration C) with solid sun shields, similar to those used for configuration H.

Configurations J and K incorporate only the sun shields and are spaced 1.0m from the building façade by means of rods at 12m centres. The sun shields in configuration J are solid, while in K they have porosity of 1:1.

Table 1. A description of the various configurations in terms of combination of the basic sunshading elements (see Figure 1).

Configuration	Element A	Element B	Element C
A	A(5m)	-	-
B	-	B	-
C	A(1.7m)	-	-
D	A(b)*	-	C(n)
E	A(b)*	B	-
F	A(5m)	B	-
G	A(1.7m)	B	-
H	-	B	C(n)
I	-	B	C(p)
J	-	-	C(n)
K	-	-	C(p)

* a spacing equivalent to the facade width, b (ie only at the vertical edges).

Tests were carried out using the University of Sydney No.1 Boundary Layer Wind Tunnel. It is of an open circuit type and is 2.4 x 2.0 x 20 m in size. The wind turbulence and velocity profiles were modelled to 1:100 scale by using the augmented method. Stathopoluos & Zhu (1988) had found that urban terrain conditions showed similar trends to open country exposure, hence data mainly pertaining to the latter were obtained. The wind speed profiles for the open country terrain, as defined by SAA (AS1170.2-1989, terrain category 2) were obtained by using floor-mounted roughness elements covering a fetch length of approximately 15m. The longitudinal turbulence and velocity, profiles are given in Figure 2. The corresponding velocity spectrum at 10m height is presented in Figure 3.

The reference model was tested for 30 different wind directions between 0 and 360 degrees generally at 15 degree intervals except in the 0 to 15 degree interval and the 75 to 105 degrees interval where it was tested at 5 degree intervals. For the models having the various appurtenances the number of wind directions was reduced to 22, concentrating on the more critical directions. The directional convention for wind angles is described in Figure 4.

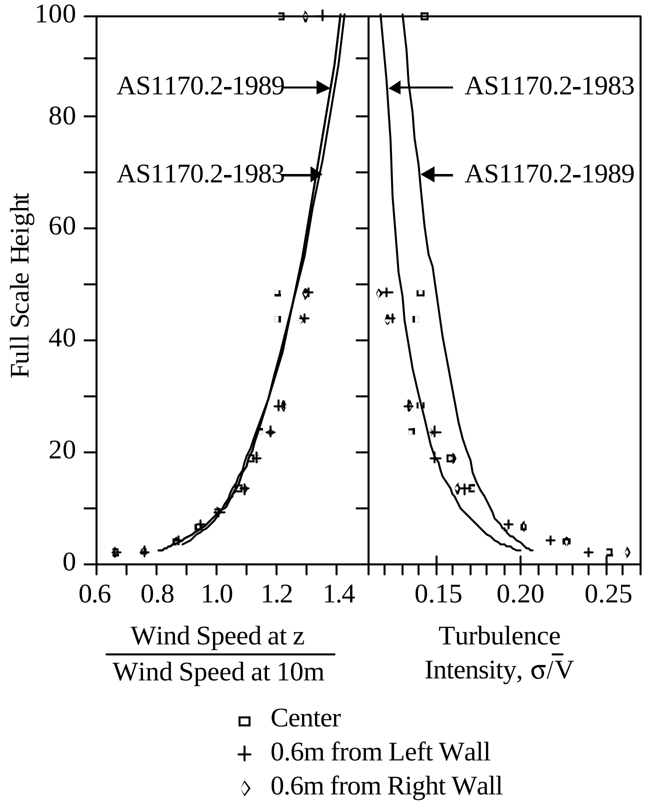

Figure 2 : Velocity and longitudinal turbulence profiles for 1:100 scale, open country terrain.

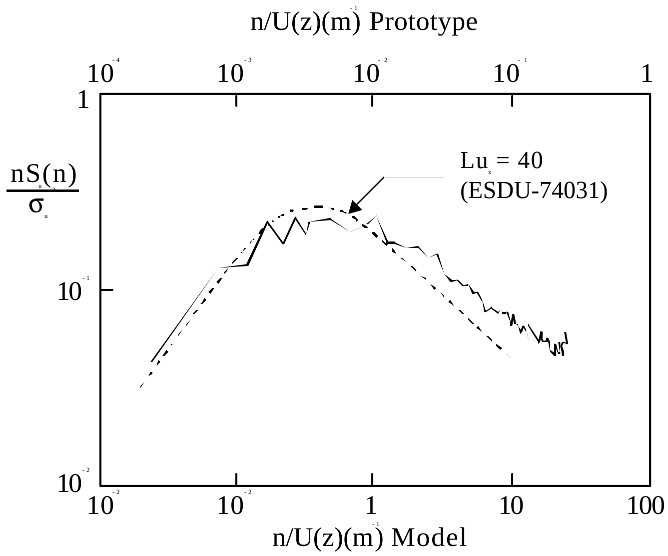

Figure 3 : Normalised power spectral Density Function for 1:100 scale, open country terrain.

2.2 *Pressure Measurement System*

In selecting the pressure tap positions, advantage was taken of the symmetry of the model. A total of 215 pressure taps were distributed over two adjacent faces of the building, both having facade elements attached to them. The layout of the pressure taps is presented in Figure 5. The PVC tubes had a calibrated length of 1.00 mm and an internal diameter of 1.3 mm. Five "Scanivalve" pressure scanning switches were connected to Honeywell Type 163

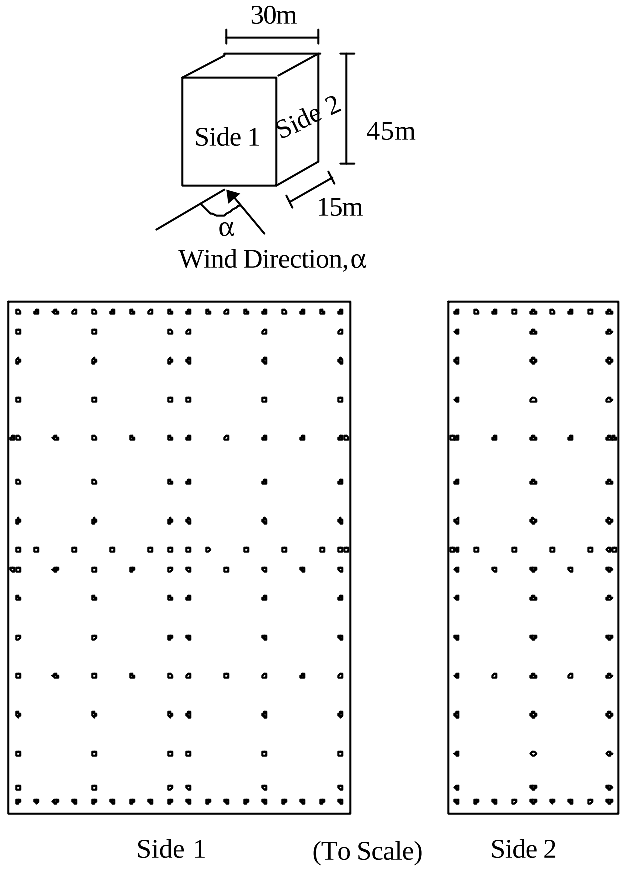

Figure 4 : Layout of pressure taps and definition of wind direction.

pressure transducers. This allowed the analogue to digital converter to sample five taps simultaneously. The pressure signal was low pass filtered at 300 Hz. The pressure measurement system was based on the leak tube system described by Gerstoft & Hansen (1987). The pressure scanning switches were connected to the pressure transducers via separate tubing, which had leak tube of 0.3mm internal diameter and 10mm in length. The purpose of the leak tubes was to attenuate peaks in the frequency response. The system was calibrated by using the method report by Holmes & Lewis (1987) and had a linear frequency response (to within 10 percent) from 0 to 300 Hz. The phase response was close to linear over this range.

2.3 *Data Acquisition and Reduction*

The signal output was digitised using a 12-bit analog to digital converter, which was powered by a microcomputer. The sampling time was 45seconds, which corresponds to approximately half an hour in full-scale time for a model of this scale. The data was analysed on line using the upcrossing method. The upcrossing technique has been described by Melbourne (1977). This method is preferred, as it requires a full-scale sampling time of only 30 minutes for sampling errors to be within 15 percent with a 99 percent confidence limit. The results obtained using the upcrossing method for a 1 second duration peak appear to be conservative with respect to the Cook and Mayne method (Cook & Mayne 1980). After comparing a number of methods of analysis of peaks, the upcrossing method seems most practical in terms of sampling time requirements and application to real cladding design parameters (Rofail & Kwok 1992).

3 RESULTS AND DISCUSSION

3.1 *Method and Analysis of Results*

Results were first obtained in terms of peak pressure coefficients using a scaled hourly mean wind speed. The pressure coefficient is defined in (1) and (2) below,

$$C_{P\,max} = \left(\frac{P_{max} - P_o}{\frac{1}{2}\rho U^2} \right) \quad (1)$$

$$C_{P\,min} = \left(\frac{P_{min} - P_o}{\frac{1}{2}\rho U^2} \right) \quad (2)$$

where P_{max} = 1 sec. maximum pressure; P_{min} = 1 sec. minimum pressure; P_o = atmospheric pressure; ρ = the density of air; U = mean wind velocity at building height; $\frac{1}{2}\rho U^2$ = dynamic pressure – static pressure at building height, H = reference velocity pressure at H.

The pressure coefficients obtained from the reference building model (with no appurtenances), using the open terrain wind model, are presented in Table 2. The effect of the various configurations of sunshading elements is made with respect to these values.

Table 2. Distribution of the peak external pressure coefficients for the reference building.

Height (m)	Windward face	Side face middle	Side face edge*	Leeward face middle	Leeward face edge*
40-45	0.9	-1.8	-2.1	-1.0	-1.0
30-40	1.0	-1.5	-1.4	-1.0	-1.0
20-30	1.0	-1.6	-2.0	-1.1	-1.3
15-20	1.0	-1.6	-2.1	-1.2	-1.2
10-15	1.0	-1.7	-2.0	-1.2	-1.2
5-10	0.9	-1.6	-2.0	-1.1	-1.1
0- 5	1.0	-1.5	-1.9	-0.8	-1.1

* The areas within a distance of b/5 from the vertical edges, where b is the width of the windward face.

It should be noted that in most wind loading codes, the prediction of the design peak pressures is based on mean pressure coefficients using gust wind speeds as opposed to the wind tunnel technique, which is based on peak pressure coefficients using mean reference wind speeds.

The slightly higher than expected peak pressure coefficients in the lower region of the windward wall and in the middle region of the side wall may be attributed to the higher turbulence intensity in the region below 10m (see Figure 2).

Global results were obtained from the largest peak pressures from the whole range of wind directions tested. The global results are based on the assumption that the probability distribution for wind load intensity is uniform with respect to wind direction. This is a reasonable assumption for the purpose of this investigation since it was found that with the exception of a few cases, the critical wind direction for each vertical and horizontal strip always lied within the same 30 degree sector. Most of the regions of critical wind direction were tested at 5 degree intervals, making use of the symmetry of the building. The critical wind directions were $0^o \pm 15^o$ (windward face) for the global maxima and were $90^o \pm 15^o$ or $270^o \pm 15^o$(side face) for the global minima. The latter two wind directions nearly always gave the same minimum. The maximum suctions on the leeward face were obtained by taking the minimum pressure from the sector $180^o \pm 15^o$.

The effect of each particular configuration is quantified by means of assessing the average variation (with respect to the reference model) in the C_p for various horizontal and vertical strips covering each face of the building and for different wind directions. The ratios of the pressures with appurtenances to those without were quite uniform. In each strip or region, deviations from the average ratio were within 15 percent, with only minor exceptions. The average ratios were rounded upwards by quoting them to the next 0.1. The average ratios will from now on be called appurtenance factors, K_{ap}. The appurtenance factor is defined by equation 3.

$$K_{ap} = \frac{\sum_{i=1}^{n} C_i / R_i}{n} \quad (3)$$

where C_i = peak pressure coefficient for a particular configuration at tap location *i*; R_i = peak pressure coefficient for the reference case at tap location *i*; *n* = number of tap locations in that region.

With the exception of configurations A and C, the adjacent face with similar appurtenances had the effect of slightly increasing windward pressures and slightly lowering leeward and side pressures. This is possibly due a local increase in turbulence due to the presence of an adjacent ‘rough’ face. For simplicity, the most conservative of either case is presented here. A comparison between the effects of the various configurations of sunshading elements indicates that certain groups of configurations have very similar effects. For simplicity, these have been grouped together under a single classification. The results are summarised in Table 3. The results are based on a flat terrain wind model.

Table 3. Appurtenance factors, K_{ap}, for various groups of configurations of sunshading elements.

a) Element Type B with or without Element Type A.

Region	Windward face	Side face	Leeward face
Middle (d/b=0.5)	1.1	1.0	1.0
Middle (d/b=2.0)	1.2	0.9	1.3
Vertical Edges*	1.2	0.8	1.0
Top Edges*	1.5	1.0	1.1

b) Element Type A alone.

Region	Windward face	Side face	Leeward face
Middle (d/b=0.5)	1.1	1.0	1.0
Middle (d/b=2.0)	1.0	0.9	1.1
Vertical Edges*	1.1	0.9	0.9
Top Edges*	1.1	1.0	1.1

c) Element Type C with or without Element Type B.

Region	Windward face	Side face	Leeward face
Middle (d/b=0.5)	1.1	0.9	1.0
Middle (d/b=2.0)	1.2	0.8	1.2
Vertical Edges*	1.1	0.8	1.0
Top Edges*	1.2	0.8	1.1

d) Element Type A with Element Type C.

Region	Windward face	Side face	Leeward face
Middle (d/b=0.5)	1.0	0.9	1.0
Middle (d/b=2.0)	1.0	0.8	1.0
Vertical Edges*	1.0	0.7	1.0
Top Edges*	1.0	0.9	1.1

* The areas within a distance of b/5 from the edges indicated, where b is the width of the windward wall.

3.2 *The effect of Elements Type A (vertical projections)*

Stathopoulos & Zhu (1988) found that by arranging the mullions such that the last mullion is attached as an extension to the adjacent wall avoids the significant increases in negative pressure (more than 150%) in the edge region for critical wind directions if the mullions were arranged otherwise. In this investigation all configurations involving mullions are arranged such that the last mullion is attached as an extension to the adjacent wall.

3.2.1 *Windward wall pressures*

The effect of the vertical elements on the windward wall pressure distribution tends to vary with the addition of other elements. The Appurtenance factors for configurations A and C were the same for the middle region. This indicates that the spacing of vertical elements has little effect on the pressures in the middle region. However, the smaller spacing result in pressures along the top and vertical edges that is 10 percent lower than those with the wider spacing. The averages of these are presented in Table 3. The same trend occurs when horizontal projections are added (configurations E, F, G).

The combination of the vertical elements with horizontal shields (configuration D) tends to offset any increase in pressure. However, the combination of vertical and horizontal projections (configurations E, F, G), increases pressures in the middle and side edge regions by a further 10 percent while the pressures along the top edge are consistently increased by 40 percent for both d/b ratios, regardless of the spacing of the vertical elements. This increase in pressure is possibly due to an upward shift in the stagnation point and the entrapment of the flow by the façade elements.

3.2.2 *Side wall pressures*

Newberry & Eaton (1974) claim that the presence of vertical projections begins to have considerable effect on the side wall pressures only for sides with a d/b ratio more than about 3. Even in such cases, they indicate that increases in pressure are unlikely to exceed 5 to 10 percent. However, in comparing the d/b ratios of 0.5 and 2.0 the results consistently indicate that although all configurations having vertical strips (configurations A, C, D, E, F, G) generally have a factor of 1.0 (no change) for d/b = 0.5, all showed reductions in the side wall pressure by 10 percent for d/b = 2.0. In addition to this, there were often significant reductions in the pressures along the top and side edges for both d/b ratios.

It should be noted that the addition of horizontal shields has the effect of reducing pressures along the edges of the side face. This is possibly due to the breaking up of the separation and reattachment mechanism (Melbourne & Saathoff, 1988).

3.2.3 *Leeward wall pressures*

Vertical projections tend to result in a 10 percent increase in suction in the middle region of the leeward wall for d/b = 2.0, again regardless of the spacing. However, as in the case of the side wall pressures, any effect of the vertical elements is offset by the addition of horizontal shields.

The addition of horizontal projections caused a uniform increase in suction for d/b = 2.0 by a further 20 percent and for d/b = 0.5 by 10 percent, regardless of the spacing. The spacing has little effect here due to lower turbulence levels and the absence of the reattachment mechanism.

3.3 *The effect of Elements Type B (horizontal projections)*

Stathopoulos & Zhu (1988) have reported that balconies with a width of up to 4 m only affect the middle region of the face causing slight decreases in pressure. Hence no attempt was made to investigate the effect of short horizontal projections.

3.3.1 *Windward wall pressures*

Newberry & Eaton (1974) found that with 'rough' facades the pressures on the edges of the windward face tend to fall off rather less than it would without appurtenances hence they proposed a minimum C_{pe} of +0.8 which is effectively a global factor of about 1.15 for the side having the larger d/b ratio. This seems reasonable for most of the configurations tested, the major exceptions being the top edges of all buildings having horizontal projections regardless of whether there is a roof above the top balcony or not. In such cases the corresponding factor are of the order of 1.5.

The effect of adding orthogonal strips has been discussed in section 3.2.1. However, the addition of horizontal shields had little effect on the windward pressures apart from increasing the pressures along the vertical edges by 10 percent.

3.3.2 *Side wall pressures*

Horizontal projections on the windward wall pressures were more effective than the vertical projections in that there was a 20 percent reduction (rather than 10 percent) in the middle region for d/b = 2.0.

This time, the effect of adding horizontal shields was more pronounced than in the case of vertical projections. Combination with horizontal shields results in a further 20 percent reduction (10 percent for mesh) in the minimum pressures in the middle region for d/b = 0.5 and a further 10 percent reduction across the face for d/b = 2.0.

3.3.3 *Leeward wall pressures*

The effect of horizontal projections on the leeward wall pressures is similar to that of the vertical projections. The combination of the horizontal projections with sun shields had the effect of evening out the pressures across the face.

The results show good agreement with the finding by Stathopoulos & Zhu (1988) that balconies with walls up to 2 m reduce minimum pressures in the middle region while balconies with high balcony walls have more pronounced effects on the edge pressures.

3.4 *The effect of Elements Type C (horizontal shields)*

3.4.1 *Windward wall pressures*

Horizontal shields alone (configurations J and K) generally tend to increase the windward pressures by about 10 percent. They only affect other configurations where d/b = 0.5. They cause a global increase (except along the top edge) in maximum positive pressures on windward walls with horizontal projections by 10 percent and a global decrease for vertical projections by 10 percent.

3.4.2 *Side wall pressures*

Horizontal shields cause significant reductions in side wall pressures, especially for d/b = 2.0. When combined with vertical projections they result in as much as 30 percent reductions in the pressures along the vertical edges.

3.4.3 *Leeward wall pressures*

Horizontal shields alone have little effect on the leeward wall pressures.

4 CONCLUSIONS

Although the facade elements tend to reduce the side wall pressures, which are the most critical in terms of cladding design, they can also significantly increase windward wall pressures.

Certain regions can be significantly affected by the addition of appurtenances. To account for these properly in the design of cladding, it is recommended that guidelines relating to the effect of these features be incorporated into wind loading codes. Different facade configurations show different effects. Although there may be room for simplification of the results presented in Table 3, a 'rough' facade approach is not recommended.

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