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A Comparison Between Wind Tunnel Cladding Pressures and Code Estimates

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SUMMARY This study presents a comparison between wind tunnel results and code estimates for three Sydney buildings with different levels of exposure. One of the buildings is approximately 30 storeys in height, located on the fringe of the Central Business District (CBD), and partially shielded by buildings to the east. The second building is medium rise and exposed from all directions. The third is 40 storeys in height and situated in the CBD with considerable shielding from surrounding buildings. The study shows that the wind tunnel results were significantly lower than the code estimates for most of the buildings' facades. The findings of the study reveal that the wind tunnel testing generally leads to a more rational design of the facade with clear implications on the cost of the cladding. The majority of the savings coming from the design of the fixtures and thickness of glazing used. The wind tunnel study also has the advantage of detecting peak pressures in critical regions that may not be adequately identified by the code.

1 INTRODUCTION

The design of a building and its cladding system is very much a function of the extreme wind induced pressures that are expected to occur within its lifetime. These pressures therefore have a significant impact on the cost of the structure. For a rational design of the cladding it is important to have a good knowledge of the wind induced local pressures that are expected to act on the building. The need for a rational design has escalated within recent years due to the popularity of tall buildings having lightweight, non-structural cladding.

In Australia wind pressures on structures are usually determined using the Wind Loading Code, AS1170.2-1989. A static analysis is used for the design of curtain walls giving estimates of localised pressure distributions. Another way these pressures can be determined is to carry out a wind tunnel pressure study on a scale model.

Improvements in the wind tunnel testing technique, combined with the integration of powerful analysis tools such as personal computers and advanced data acquisition instrumentation, has meant that wind tunnel pressure studies are able to provide an accurate picture of the pressure distribution on a building.

2 BACKGROUND

2.1 Wind

The wind loading of structures is a complex phenomenon as wind is a vast array of eddies with varying sizes and rotational characteristics. These eddies move along relative to the earths surface and produce gusty or turbulent behaviour. In the lower levels of the atmosphere a boundary layer forms which is largely a function of local surface characteristics such as the existence of hills, valleys, vegetation, and buildings. When the wind interacts with structures it exerts pressures which are not steady but highly fluctuating. This fluctuation is due to the gusty nature of the wind and local vortex shedding at the edges of the structures (1), as well as wakes being set off by nearby buildings (if any).

The pressure generated by the wind is a very important criterion for the design of buildings and their facade. To determine the event of these pressures wind flow can be analysed as statistical variations which include events that are expected over a period of time. The design wind accounts for a statistical recurrence event usually over a 50 year period (for permissible stress design) which represents the life of the building. For ultimate limit states design, a return period of 1000 years is used.

2.2 Wind Pressure Distributions Around Buildings

Wind, with its turbulent nature produces vortex shedding, and separation effects. This results not only in overturning and shear effects but also induces dynamically fluctuating loads on the overall building structure and on individual cladding panels.

Wind tunnel studies that have previously been conducted on scale models of buildings have produced evidence that three different pressure zones are developed when wind acts on a tall building (2). These are listed below.

- *Positive pressure zone on the upstream face.* Winds acting directly on the windward face produce positive pressures and normally increase in magnitude with height.
- *High negative pressure zones at the upstream corners of the side walls.* Pressures produced at these corners are much in excess of the normal pressure further down the face and this can be evidenced by damage to corner windows and eaves in buildings. This occurrence is due

to local vortex shedding at the edges. The negative or suction pressure decreases in magnitude further down the side wall face in the direction of wind flow. AS1170.2-1989 (3) provides pressure coefficients that decrease with horizontal distance from the windward edge.

- *Negative pressure zone on the leeward wall or downstream face of the building.* The suction pressures produced are typically less than the high corner pressures experienced at the leading edge of the side wall. Leeward wall pressures rarely govern the design as side wall pressures are typically higher. Leeward wall pressures still however need to be taken into consideration as peculiar building geometries or surrounding buildings may alter the expected pressure conditions.

2.3 The Australian Wind Loading Code, AS 1170.2-1989

This is the most commonly used method of determining peak design wind pressures in Australia. For the purpose of this paper a Detailed Static Analysis is used in a comparison with wind tunnel test results. This code pressure prediction includes peak gust wind speeds which have been modified with appropriate multipliers for terrain, building height, topography, shielding and building geometry.

2.4 The Wind Tunnel

Buildings with unusual geometry normally warrant a wind tunnel study. The wind tunnel provides a means of studying as precisely as possible the effect of natural wind on the building in question. Figure 2.1 shows a typical building model being tested in Windtech's boundary layer wind tunnel. Note the use of vertical spires and barriers upstream in conjunction with roughness blocks on the floor. These are positioned upstream so as to simulate the incoming boundary layer flow.

The following is a list of key areas that are of particular importance to high rise building design and are able to be investigated with wind tunnel pressure studies.

- The influence of nearby structures and their effect on the behaviour of the proposed building
- Effects of boundary layer profiles that are a function of the land topography and terrain.
- Pressure distributions on the building as related to local vortex shedding and flow separation
- Dynamic response of the building and loads on cladding

2.5 Cladding

The use of light-weight cladding is very popular in the design of tall building facades. Lightweight facades are non-load-bearing and are designed to resist peak wind pressures. They also have strong visual impacts on a building and significantly define its aesthetics.

Glass is the most commonly used material in these type of facades. The yield strength of glass is not known with sufficient accuracy to base a design upon. Instead glass is designed on the basis of an acceptance criteria which is based on probabilities of failure as opposed to strength. In this respect it is important that the local wind environment and its associated pressure distributions on the building are determined accurately in order to design the glass rationally to make a cost effective and safe design.

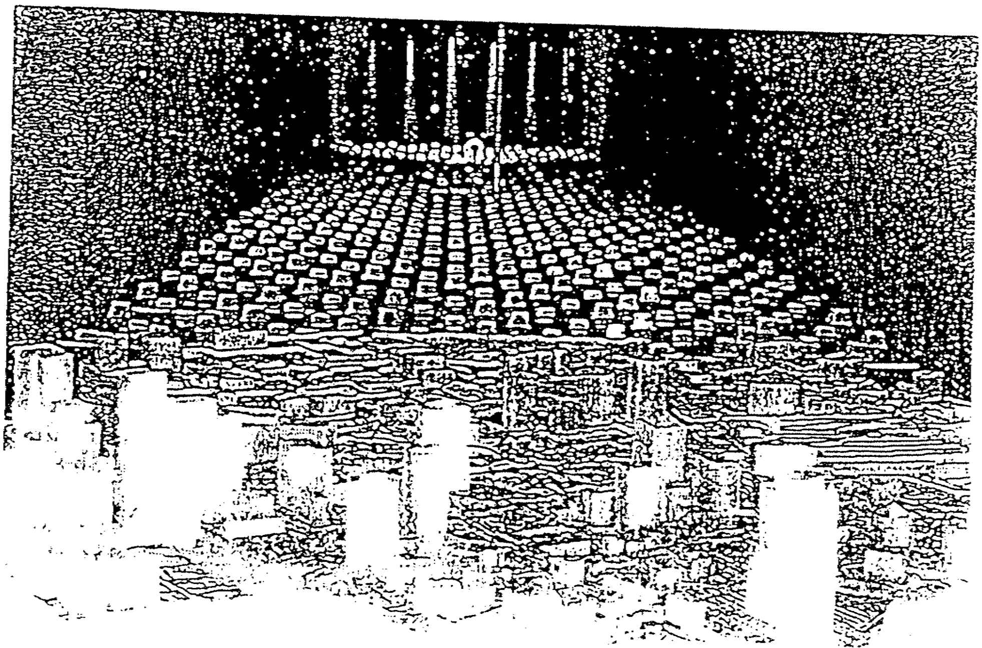


Figure 2.1 Boundary Layer Wind Tunnel

3 EXPERIMENTAL SETUP AND TESTING

3.1 Testing Procedure

The testing program adopted can be summarised as follows.

- Set up a model of the building to an appropriate scale (1:500) and fit it with pressure taps covering the external face of the building. These taps will give points of pressure which can then be used to determine the design loads to be expected on the cladding. This scale is determined by the cross sectional area of the wind tunnel. Note that within certain limits the effect of scaling on the results is not significant (4).

- Model the surrounding topography and buildings to a radius of approximately 500m placing the study building in the centre.

- Model the upstream conditions which include vertical spires, barriers, and roughness blocks. The extent of this modelling will be dependent on the terrain category required to be developed.

- Establish design wind speeds. The directional distribution of the local wind speeds can be obtained from the Wind Loading Code, AS1170.2-1989. Then scale the prototype speed to a modelled speed.

- Test the model in 36 wind directions at 10 degree increments. Obtain peak and mean global point wind pressure measurements. Retest at intermediate wind directions (commonly called 'directional increment chasing') where pressures are deemed to be critical.

- Plot pressure contours (or block diagrams) about each face of the building. These pressure contours or blocks can then be used to carry out the design of the cladding.

3.2 Model Description

All three models were at a scale of 1:500 and fitted with approximately 200 to 300 pressure taps. Surround models incorporate the neighbouring buildings and local land topography to a radius of 500 m from the pressure taped building. Varying roughness blocks, vertical spires, and barriers, as shown in figure 2.1, are used to model the wind into an appropriate boundary layer flow before it encounters the close proximity model. The model setup for each of the three buildings is described below.

CASE 1

This building is situated on the north western fringe of the CBD. The 90 degree sector from north-west to north-east was modelled to an AS1170.2-1989 Category 2 (open terrain) representative of wind coming in over Sydney harbour. A Category 3 (suburban) upstream terrain was used for the rest, representing flow through the city. The close proximity model was subsequently used to model the expected Category 4 (city centre) flow immediately around the central building (5).

CASE 2

Here the building lies well outside and to the west of the CBD. The model was consequently placed in a Category 3 wind terrain to match the north, south, and west sectors, while a Category 4 boundary layer flow was used to model wind flowing over the city. Once again the surrounding model was relied on to match the flow patterns immediately around the building.

CASE 3

This building lies well within the CBD, being shielded by tall buildings from all directions. The model was tested in a Category 3 terrain, while the close proximity model was relied on to develop the required Category 4 flow.

4 DERIVATION OF THE PEAK PRESSURES

4.1 Method Of Analysis Of Results

A detailed analysis which involved 36 wind directions at 10 degree increments was carried out. For cases 2 and 3 directional increment chasing was carried out at critical wind directions. Peak pressures were subsequently obtained using the standard upcrossing technique. For this method the pressure range of each signal is divided into small bands. The data consists of instantaneous values or crossings with positive slope (or for minimum pressures a negative slope) made by the signal at different levels of pressure represented by different bands. The range of pressures is divided into small bands. The data contains a number of crossings with positive slope at different levels of pressure (6). The term 'positive slope' refers to the direction of increasing positive pressure or decreasing negative pressure (7). This data is used to carry out a statistical analysis of the pressure signal, assuming a Poisson distribution (4). The data is initially fitted to a Poisson distribution and then Fisher Tippett type I parameters are derived in order to calculate peak design pressures.

A sampling time of approximately 30 minutes in prototype scale was adopted. The signal was low pass filtered at between 300 to 400 Hz as the pressure measurement system has a flat response up to 300 Hz and no resonant peaks up to 400 Hz. The analogue signal obtained from the pressure transducers connected to the pressure taps was digitised at a rate of 2500 samples per second. The data was subsequently analysed in digital form using the upcrossing method (7)

Wind tunnel results are produced in normalised form (pressure coefficients), with reference to a velocity pressure measured upstream of the proximity models and free from interference by wakes in the boundary layer flow. This reference velocity pressure is related to a reference pressure at the building height. The actual pressures (in kPa) for permissible stress design were derived by multiplying by the pressure coefficients with the equivalent full-scale reference pressure in AS1170.2-1989.

The results from the wind tunnel and Code will be presented in terms of permissible design wind pressures.

Typically, the cladding pressures are presented in the form of pressure contours or block diagrams. Block diagrams are normally used for design purposes as they neatly define different pressure regions on the building face. In cladding design, for instance glass thickness, only a few pressure regions will be specified. This may perhaps lead to a conservative design but for all purposes it is not practical to have too many pressure regions. This can therefore lead to higher construction and labour costs with a lower margin of safety due to the likelihood of incorrect glass thickness placement.

The Australian Wind Loading Code AS1170.2-1989 predictions and the wind tunnel pressure results (as shown by pressure zones) for peak pressures are shown in figures 4.1 to 4.6. Maximum peak pressures and minimum (suction) peak pressures are produced and these plots can be used in cladding design. The figures shown are for random faces of the buildings tested. These results generally give the biggest difference between the wind tunnel results and the Codes predictions. They thus become good cases to base a comparative study upon. General comments will also be made as to the pressures experienced on the building faces not shown in the figures.

It should be noted that these model based facade pressures are external pressures only. Allowance for an internal pressure should be made. For design purposes this internal design pressure can be based on the requirements of the Wind Loading Code AS1170.2-1989.

4.2 Comparison Between Wind Tunnel Test Results and Code Estimates

The following is a summary of the comparative results of maximum and minimum pressures for the three cases.

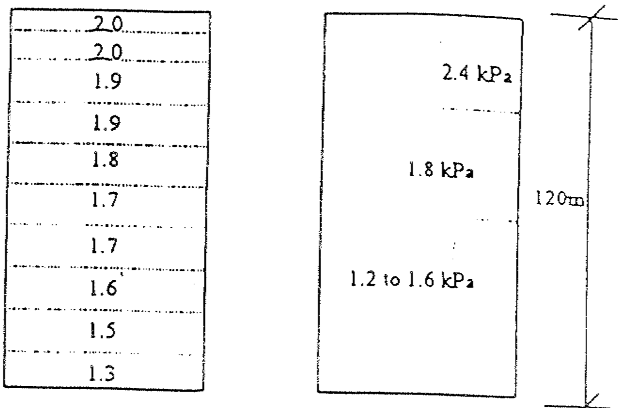
Maximum Peak Design External Pressures.

Case 1

Since Case 2 lies on the Western fringe of the CBD the incident wind from the west flows relatively unimpeded. Large pressures which were measured were consistent with the Codes prediction as can be seen in Figure 4.1, maximum peak pressures. For the other faces, pressures were measured that were consistently lower than the Code. Occasionally high pressure regions were recorded but these were localised occurrences and not deemed to affect the design considerably.

Case 2

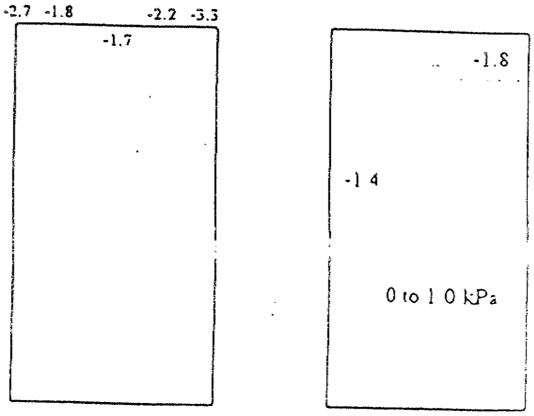
The wind tunnel produces maximum pressures that were consistently lower than the codes predictions. Figure 4.3 shows the most critical wind tunnel pressures and these are



a) Code b) Wind Tunnel

West Elevation (Maximum Peak Pressures (kPa))

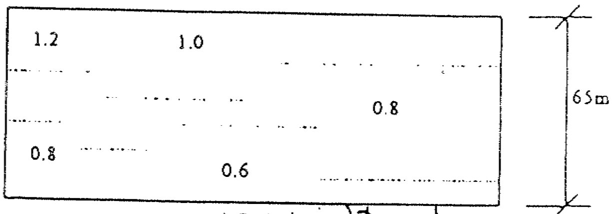
Figure 4.1 Pressure Plots for Case 1



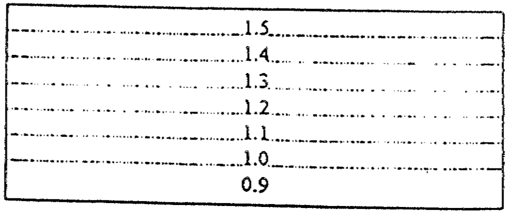
a) Code b) Wind Tunnel

North Elevation (Minimum Peak Pressures (kPa))

Figure 4.2 Pressure Plots for Case 1



a) ~~Code~~ Wind tunnel



b) ~~Wind Tunnel~~ Code

West Elevation (Maximum Peak Pressures (kPa))

Figure 4.3 Pressure Plots for Case 2

still below the codes.

As to be expected the largest maximum pressures have occurred on the west face and this is consistent with highest directional wind speeds coming from the west.

Case 3
For all four faces the maximum pressures from the wind tunnel were consistently lower (by approx. 15 percent). Figure 4.5, maximum peak pressures, shows where a localised region produced pressures slightly higher than the codes prediction (approx. 6 percent). Even though this difference is relatively small it implies that the wind tunnel results provide a rational as well as a safer representation of the wind pressure distribution on the building facade.

Minimum Peak Design External Pressures

Minimum pressures (suctions) usually govern the design of cladding. Owing to the uncertainty of the nature and magnitude of winds in regions of high suction's the code assigns a suitable multiplying coefficient. This local pressure factor reaches a value of up to three in critical regions (refer clause 3.4.5 in AS 1170.2-1989). The following comparisons will show that the code often tends to be conservative. However, it should be noted that these high Code values provide a suitable margin of safety against the underestimation of extreme localised pressures.

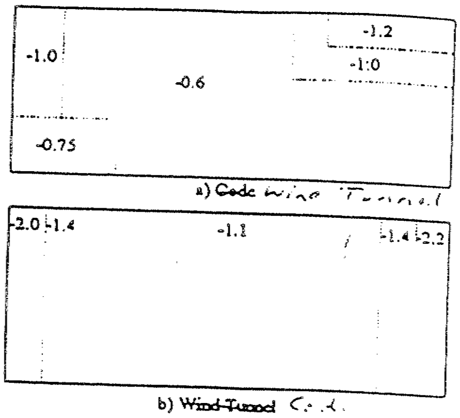
Case 1
Figure 4.2, minimum peak pressures, is typical of the sort of pressure reductions the wind tunnel provided. The south face pressures however, which have not been shown, were slightly higher then the codes predictions. The increase can be attributed to local effects such as interference from nearby buildings and land topography.

For case 1 the wind tunnel was producing pressures in some localised regions that were higher than the codes. Overall, the pressures were lower but these 'hot spots' indicate that the wind tunnel is able to detect high pressures derived from intricate wind profiles around the area. Even though the code seems to provide pressures that are consistently higher than the wind tunnel, it maintains a suitable factor of safety against underestimating these 'hot spots'.

Case 2
As with the maximum pressures, in Figure 4.4, the wind tunnel produces minimum pressures that are consistently lower (30 to 45 percent) than AS1170.2-1989.

For case 2, and its surrounding environment, it seems that wind tunnel test results give lower pressures overall than the code. The implications of these reductions will be a direct reduction in the cost of building materials and hence a more cost effective design.

Case 3
The results shown in figure 4.6 are typical of the sort of reductions obtained from the wind tunnel over the code. The

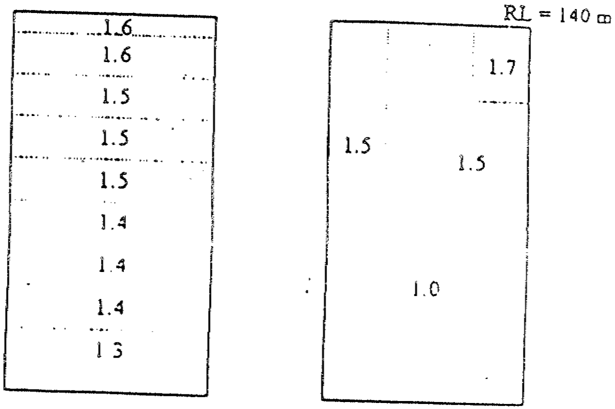


a) ~~Code~~ Wind Tunnel

b) ~~Wind Tunnel~~ Code

West Elevation (Minimum Peak Pressures (kPa))

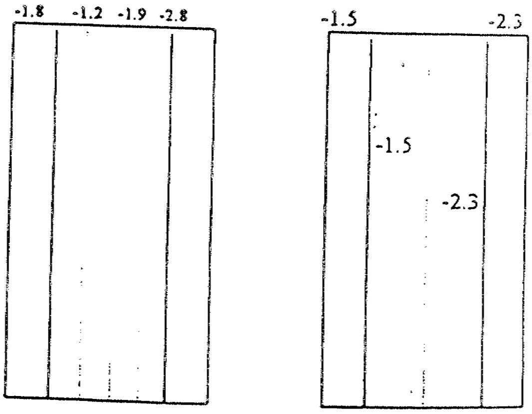
Figure 4.4 Pressure Plots for Case 2



a) Code b) Wind Tunnel RL = 80 m

West Elevation (Maximum Peak Pressures (kPa))

Figure 4.5 Pressure Plots for Case 3



a) Code b) Wind Tunnel

North Elevation (Minimum Peak Pressures (kPa))

Figure 4.6 Pressure Plots for Case 3

pressure distributions are consistent with what is expected (ie. high pressures at the edges).

This building is shielded by tall buildings in all directions. With this shielding comes a retardation of the incoming wind and a reduction of the pressures. For the code estimate a shielding multiplier of 0.95 was used with category 4 flow conditions.

4.5 Cost Comparison

Wind pressures have a direct bearing on the selection of glazing used. The design of glass is typically based on the following criterion:

- wind pressures (magnitude and direction required)
- size of panel (area of glass)
- fixity (2 or 4 sides fixed)
- design stress of the glass
- thermal stresses (differential stresses set up from heating and cooling of window framing)
- acoustics

The following is a preliminary estimation of potential savings in glass by considering the wind tunnel results and code estimates for the design of the glazing. For the purpose of this paper, glass selection will be based on wind pressure, size of panel, and fixity only. Design will be based on glass design charts in the Glass Installation Code AS1288-1989 (8).

For the purpose of a typical design the following glass and dimensions will be used.

- laminated toughened glass in extreme external pressure cases.
- heat strengthened float glass for the bulk of the glazing.
- double ply glazing for vision panels and single ply for spandrels.
- typical window dimensions are 1.3m by 2m for the vision and 1.3m by 5m for the spandrel panels.

Preliminary calculations on the above criteria indicate that for Case 1 a 16% saving in the cost of the glass will be possible when using the wind tunnel results over the codes estimates. This amount of saving will more than compensate for the cost of the wind tunnel study. Savings will also be possible for case 2 and 3.

5 CONCLUSIONS

The design of a building structure and its cladding is usually based on wind pressures predicted from the Wind Loading Code AS1170.2-1989 using a Detailed Static Analysis. The wind tunnel testing technique also allows the determination of pressures on structures. Both methods give point pressures or localised pressure distributions. A comparative investigation was subsequently carried out between the wind tunnel testing technique and the Code predictions and an assessment on the relative cost aspects was also addressed.

This comparative study was conducted on three buildings in the CBD all with different heights, plan dimensions, degree of shielding, and upstream terrain categories.

The results of this study showed the following:

- The Wind Loading Code gives predictions for peak maximum and minimum (suctions) pressures that were consistently higher than those from the wind tunnel. The Code tends to be conservative as it must account for a wide range of building geometries and topographical features.

- The wind tunnel testing technique is able to provide a more accurate assessment of the wind flow around a building and the resulting pressures. Less assumptions are used than in the code giving a higher confidence level, lower safety factors and a more rational design.

- The code is suitable for the majority of structures. However, due to the ever increasing competition for economical designs the wind tunnel testing technique should be considered as a viable alternative to the estimation of design wind pressures due to the potential cost savings in materials it offers.

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