Loading of a very tall building in a simulated downburst wind field

M. Mason[1], **G. Wood**[1]

[1]Wind Engineering Services, The University of Sydney, NSW 2006, Australia

Introduction

Thunderstorm downbursts are important for wind engineers as they have been shown to produce the design wind speeds for mid to high return periods in many regions of Australia [1]. In structural design codes (e.g. AS/NZS1170.02-02) an atmospheric boundary layer (ABL) is assumed, and a vertical profile is interpolated from recorded 10 m wind speeds. The ABL assumption is however inaccurate when considering the complex structure of a thunderstorm outflow, and its effects on engineered structures. Several researchers have shown that the downburst, close to its point of divergence is better represented by an impinging wall jet profile than the traditional ABL. Physical modelling is the generally accepted approach to estimate wind loads on structures and it is therefore important to physically model the thunderstorm downburst so that its effects on engineered structures may be studied. An advancement on the simple impinging jet theory, addressed here is the addition of a pulsing mechanism to the jet which allows not only the divergent characteristics of a downburst to be produced, but also it allows the associated leading ring vortex to be developed. The ring vortex modelling is considered very important for structural design as it is within the horizontal vortex that the largest velocities occur [2]. This paper discusses the flow field produced by a pulsed wall jet, and also discusses the induced pressures that this type of flow has on a scaled tall building.

Modelling

To simulate downburst flow, the impinging wall jet at The University of Sydney (Figure 1) (D=0.31 m) was fitted with a pulsing mechanism situated at the outlet. For this research the pulsing mechanism was a simple thin latex membrane. The pulsed flow was produced by stretching the membrane across a 0.5 m circular hole cut into a support board positioned approximately 10 to 20 mm from the outlet of the jet. When the jet was turned on, the small gap between the membrane and the outlet of the jet allowed flow to be diverted away from the testing surface thus leaving an essentially still field in that region. The membrane was stretched to such an extent that when the jet was impinging it, flexure at the mid point was approximately 20-30 mm causing a small initial dome shape. The membrane was then burst with a blade connected to a thin metal rod able to be held so that only the rod was disturbing the outlet flow. The time taken for the membrane to retract out of the jet flow was less than 0.066 seconds (time for 1 camera frame) which is considered an improvement on the previously tested aperture pulsing mechanism which took approximately 0.15 seconds.

Tests were performed simultaneously to measure both a vertical velocity profile and also to measure induced pressures on the surface of a scaled building (Figure 2). Velocities were measured with a TFI 4 tap Cobra probe which allowed both flow magnitude and direction to be calculated. Velocities were sampled at 1250 Hz. Pressures were measured simultaneously on either the windward (front), or side face of the building. The model and Cobra probe were positioned equidistant from the jet centre line on opposite sides of the outflow. Pressures were sampled at 1000 Hz, and no appreciable amplitude magnification below 300 Hz was calculated for the tubing system.

Results and Discussion

Due to the time involved in making the membranes it was decided that the vertical profile and induced model pressures would only be measured at the radius where the maximum peak velocity due to the transient vortex occurred. It was determined that with the testing surface set 465 mm (Z/D=1.5, based on an average cloud base height determined by Hjelmfelt [3]) from the jet outlet the maximum peak velocity occurred at a radial distance of 310 mm (X/D=1.0) from the jet centre line (determined from recorded peaks at an elevation of 10 mm, which was the approximate height to peak in steady flow). Thus, velocity measurements were taken for a range of elevations at this radial position. Figure 3 shows the normalized scatter of peak velocity values obtained over the elevation range of $0.003 \leq Z/D \leq 0.2$ ($1\text{mm} \leq Z \leq 60\text{mm}$) and also an averaged peak profile through these points. The peak velocity is the non-averaged experimental 1/1250 second peak, and using the scaling factors discussed at the end of this paper approximately equal to a 1 second gust. The average peak was determined by extracting the peak velocity value from each recorded time history (refer Figure 6) within the region associated with the passage of the horizontal vortex (simulated region, Figure 6) and averaging these values with others recorded at the same point. The obtained profile shows what appears to be a small boundary layer type increase in velocity below Z/D=0.02, with a decrease in velocity with elevation above this point. This type of profile is similar to what would be expected for peak velocities if it is assumed that all peaks occur directly below the vortex core (which is what is expected). Simple vortex theory suggests that for a forced vortex the velocity will increase in direct proportion to the distance from the vortex core. This would not strictly be the case here as the vortex impact with the surface would alter the velocity distribution within it and thus produce a non-linear relationship as is observed by the slight curvature in the profile.

The model shown in Figure 2 (122 mm x 16 mm x 16 mm), with tap layout indicated, was submerged in the simulated downburst flow in two configurations, the first was with the tapped face as the windward face, and the second with the tapped face positioned as a side face. The arrows in Figure 2 indicate the direction of flow for each of these tests. Figure 4 shows peak positive and negative pressures induced on the front face by the transient downburst vortex, with again an averaged peak profile indicated. The pressure coefficients, Cp_{jet}, are referenced to the steady impinging jet outlet velocity (13.35 m/s) with the board in position at Z/D=1.5. The positive peaks over the region of the building below Z/D=0.2 indicate a close to linear decrease in pressure with elevation. The almost linear relationship observed would suggest, based on quasi-steady flow that the velocity profile shown in Figure 3 may in fact be decreasing as a second order polynomial. The negative peaks in the region below Z/D=0.2 are quite benign, which is what would be expected when considering the initial impact of wind with a structure. Above Z/D=0.2 the pressure field is much different, and predominantly negative peaks are the governing loading cases due to the vortex's passage. The fact that negative peaks are now so high, suggests that the flow has reversed directions, which in the case of a horizontal vortex, means that the building is now in the upper half of the vortex section (i.e. above the vortex core). Thus it is suggested that the vortex core is located at approximately Z/D=0.2. This point is marginally higher than that suggested in [4], the discrepancy however can be associated with the differing types of flow pulsing. The averaged negative peaks reach an absolute magnitude of approximately half those observed below Z/D=0.2, it would be expected that these negative peaks would be of lower absolute magnitude than the positive peaks due to inherent bluff body effects associated flow reversal, and also there was no flow confining surface to "squash" the dimensions of the vortex, as was the case for the base of the model. Entrainment of ambient surrounding fluid would also serve to alter the conditions at the vortex boundary, which may suggest why the variability of peaks is so high for the top point on the building. The average instantaneous pressure profile is also indicated in Figure 4 for both the maximum positive pressure case, and also the maximum negative pressure peak. It can be seen that these profiles are almost identical, and follow the maximum positive pressure and maximum negative profiles closely. This relationship again suggests that the maximum peaks over the building occur close to within a vertical plane taken through the vortex core.

To further investigate the instantaneous loading profile over the height of the building a temporal peak profile (time between peaks at different points) has been determined for both the front face (Figure 5a), and the leading edge of the side face (Figure 5b) with respect to the velocity peak at the lowest point on the building (max positive peak). The dimensionless time (t^*) given in Figure 5 is the recorded model time (t) before or after the peak at the reference tap, normalized by a time scaling factor, U_j/D, where U_j is the steady jet outlet velocity and D is the jet diameter. A negative t^* indicates the peak at that tap occurred prior to the peak at the lowest tap on the model, and a positive t^* suggests the peak at that tap trails the reference tap, and therefore if $t^*=0$ that tap is fully correlated with the reference point. The top three sets of points on the windward face are the time to the negative peak, while the remainder are to the positive peaks, while for the side face all times are to the negative peak. The averaged peak profile looks similar for both the front and side faces suggesting that a peak on the front of the structure approximately correlates to a peak on the side of the structure all be it of the opposite sign. It is noted that on the front face the second tap from the bottom (13 mm from the surface) and also the top three taps (negative peaks) on average peaked prior to the reference tap. The positive peaks above the second tap then occur fractionally later with an increase in elevation. The negative peak correlation on the side wall followed a similar pattern, but in this case taps at Z=13, 22, and 30 mm from the surface as well as two of the three top taps, on average, peaked prior to the reference tap. Putting these correlations into context however, if scaled (refer to next paragraph) to full scale times, a t* value of 0.2 (t_m=0.0046 s) represents 5.7 seconds, and the buildings height of 122 mm is approximately 590 m, thus in practice reducing the correlation of peak loading essentially to a fully correlated system for both front and side faces. A full correlation of peak pressures would again support the theory that the peaks are occurring in a vertical plane through the vortex core.

Finally Figure 6 has been included to compare a full scale time history recorded at Andrews AFB in 1983 with averaged experimental velocity data recorded at Z=1 mm. The scaling factors used were Lr=1/4838, Vr=1/3.93, and Tr=1/1230, with L based on a full scale downburst diameter of L_p=1500 m, and V_p=67 m/s (peak velocity) recorded for this particular event. An excellent comparison between the two sets of data can be seen in the simulated region, with the acceleration characteristics being particularly encouraging.

[1] Holmes, J.D., "A Re-analysis of Recorded Extreme Wind Speeds in Region A," Australian Journal of Structural Engineering, Volume 4, pp. 29-40, 2002

[2] Fujita, T.T., "Downbursts: Meteorological Features and Wind Field Characteristics," J. of Wind Engineering and Industrial Aerodynamics, Vol. 36, pp. 75-86, 1990

[3] Hjelmfelt, M.R., "Structure and Life Cycle of Microburst Outflows Observed in Colorado," J. of Applied Meteorology, Vol. 27, pp. 900-927, 1988

[4] Mason, M, & Letchford, C., "Pulsed wall jet simulation of a stationary downburst: Part A, Physical structure and flow field characterization," Submitted to J. of Wind Engineering and Industrial Aerodynamics, June 2004.

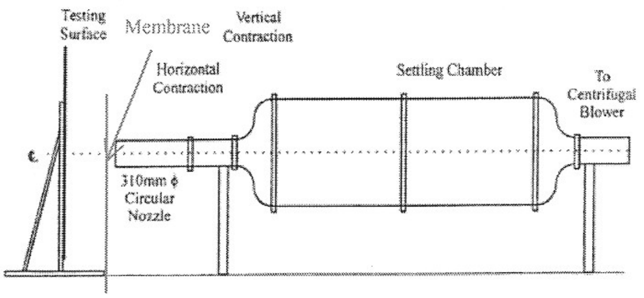

Figure 1: Impinging jet setup and positioning of membrane.

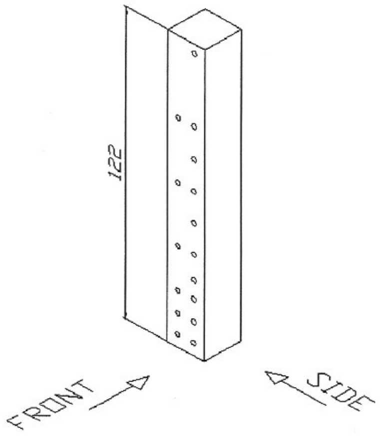

Figure 2: Tested model and tap layout.

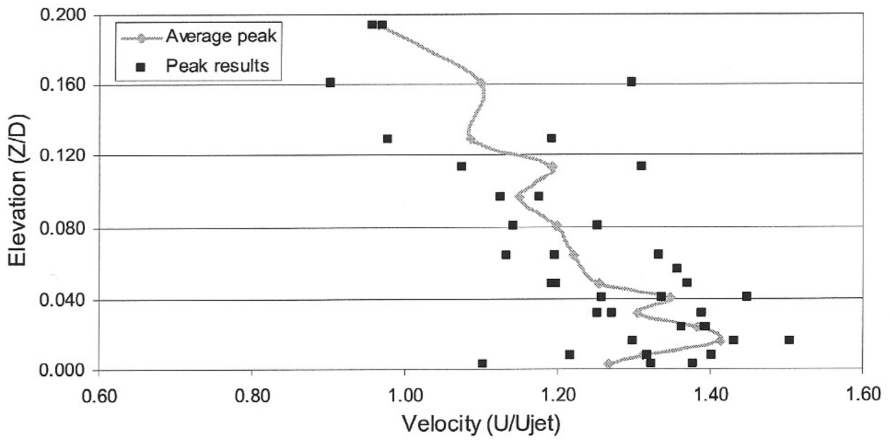

Figure 3: Normalized vertical velocity profile at X/D=1.0, Z/D=1.5.

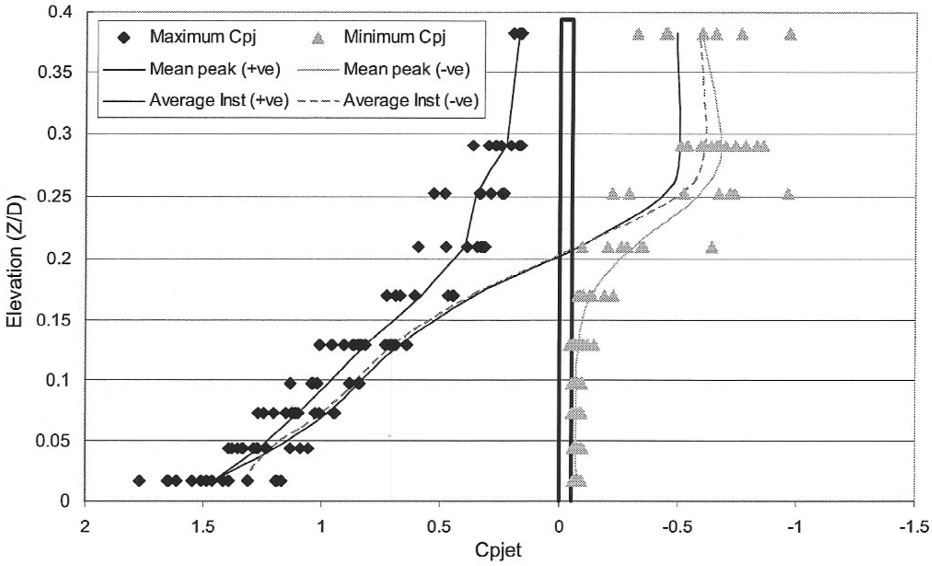

Figure 4: Induced pressures on the front face of a tall building in simulated downburst winds

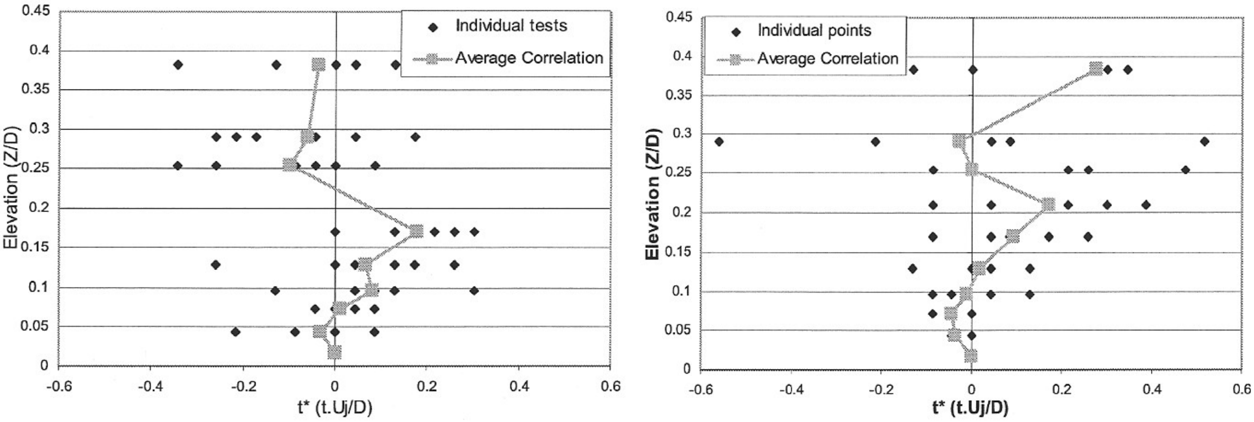

Figure 5: Peak pressure correlations up the building (a) Front face (b) Side face

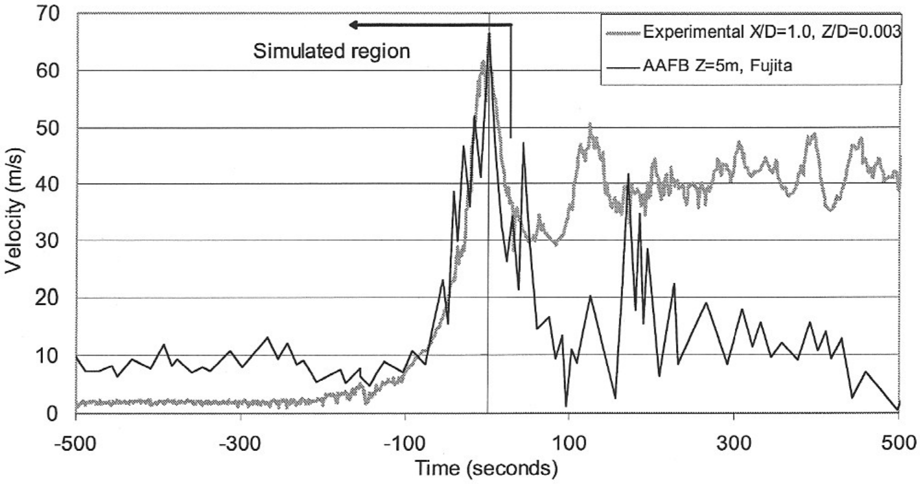

Figure 6: Time history comparison between Andrew AFB microburst recorded at Z=5 m, and time history recorded experimentally at Z=1mm (full scale Z=5 m)