New Developments in Commercial Wind Engineering

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ABSTRACT: The primary intent of this invited presentation at the International Workshop on Wind Engineering and Sciences is to discuss new developments in commercial wind engineering, to pose some questions that may (hopefully) lead to some conversations between attendees, and perhaps to speculate on the future of our peculiar specialty. Many of us gather every four years at the International Conference on Wind Engineering in order to discuss the minutia of wind engineering developments, but what is happening to our field in a holistic sense? What could we do to make our work more useful to the public or our clients? Some items presented herein are minor and can easily be dismissed as just my idiosyncratic view of consulting, engineering and ethics. However, some issues are definitely more serious and need to be tackled by consulting wind engineers, and to some extent researchers, in the near future. Whilst attempting to develop some points of consequence, nay controversy, perhaps we can have some fun too.

1 MODEL CONSTRUCTION

In recent years the use of stereolithography (SLA) to build wind-tunnel pressure models has largely superseded the traditional, machined Plexiglas pressure model. As architectural designs become more complex, the ability to generate the dual-curvature shapes using programs like AutoCAD and SolidWorks allows the pressure tap paths to be incorporated into the design before the laser-induced growth of the model commences in the stereolithography vat (Figure 1). There is some skill in knowing the best way to design the pressure model components for useable pressure path lengths, strength in construction and optimal material volume, but the competitive cost of this technique means that about 80% of pressure models are now built using this method at CPP Inc. An example of a finished, curved, SLA, pressure model is shown in Figure 7. The ability to make very thin shells for lightweight high-frequency force balance (HFFB) models is also a useful advantage for this model construction technique (see Figure 8).

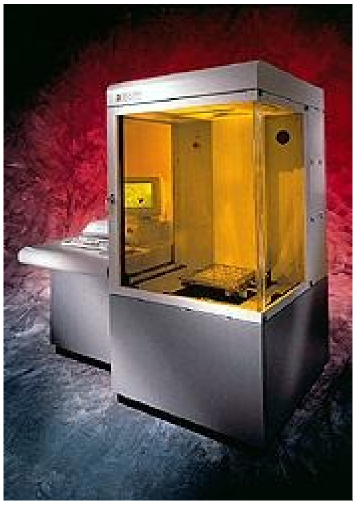

Figure 1: The laser booth and operational console of a stereolithography machine.

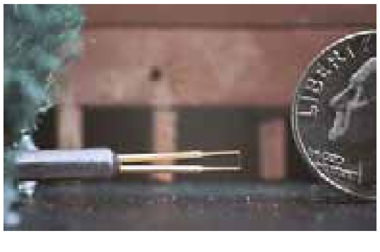

Figure 2: The hot-film anemometer has traditionally been used to collect turbulent velocity data in the wind tunnel.

2 VELOCITY MEASUREMENTS

The measurement of mean and peak wind speeds in the wind tunnel has traditionally been done with the hot-wire or hot-film anemometer; the former being more responsive, but less robust. This well established technology (Schubauer and Klebanoff, 1946; Sandborn, 1972 and 1981) shown in Figure 2 now has some competition from the highly-responsive, multi-hole pressure probes, such as the Cobra Probe in

Figures 3, 4 and 6. These devices typically have between 4 and 13 holes in the head along with the miniature pressure transducers (yielding good frequency response), and can measure speed and direction over angular ranges that incorporate some level of reverse flow in separated regions. The ability to respond to the reverse flow condition depends to some degree on the number of holes (and so transducers) in the probe design. The software that comes with the probe evaluates the many pressure signals to yield a time-series of flow speed and direction. Figure 5 shows profiles developed near, and downwind from, a 90-degree step. In recent years many commercial laboratories have discovered the usefulness of the multi-hole pressure probe, even in highly turbulent flows. The wind-engineering community is still evaluating this relatively new technology, but it is likely to be the way of the future for mean and gust velocity measurements in the wind tunnel.

Figure 3: Four-hole Cobra probe in use at HKUST (after Dr. Peter Hitchcock).

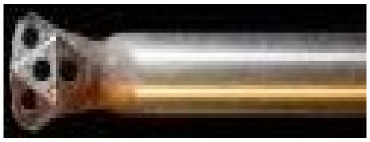

Figure 4: Close-up of a four-hole probe (after Turbulent Flow Instrumentation Pty. Ltd.).

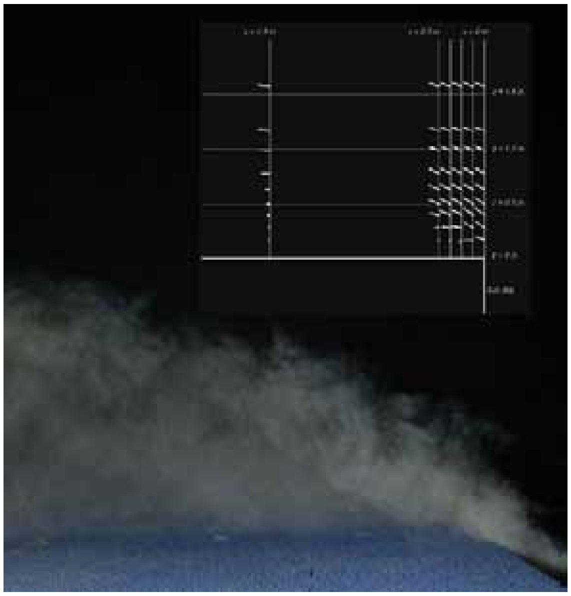

Figure 5: A composite photograph of flow visualization over a vertical escarpment and the vectorized mean velocity profiles measured by a multi-hole pressure probe. The scales of the flow visualization and profile images are roughly the same (after Noriaki Hosoya, CPP Inc.).

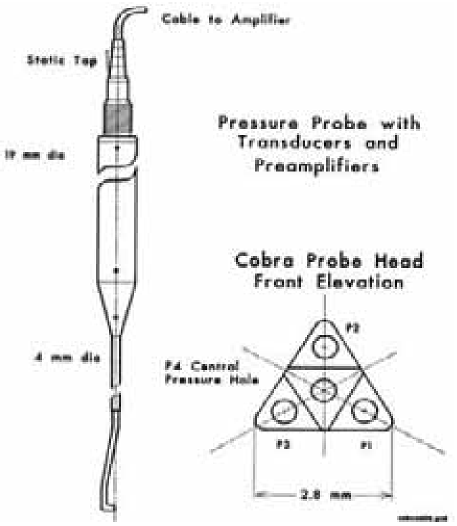

Figure 6: Schematic of the four-hole Cobra Probe (after Turbulent Flow Instrumentation Pty. Ltd.).

Laser velocimetry (Figure 7) has been used routinely in fluid mechanics for at least two decades, but it is now starting to appear in the commercial side of wind engineering to help clients with particular problems. Figure 7 shows this device being used to define the wind speeds and directions around an open lattice structure at the newly refurbished Pennsylvania Railway Station in New York City. These fine measurements can be made at the location of the lattice or open structure without interfering with flow that was being measured. Laser velocimetry is usually the more expensive option, but with a good understanding of the winds around the lattice and knowledge of the member shapes the structural wind loads can be better assessed by the structural engineer.

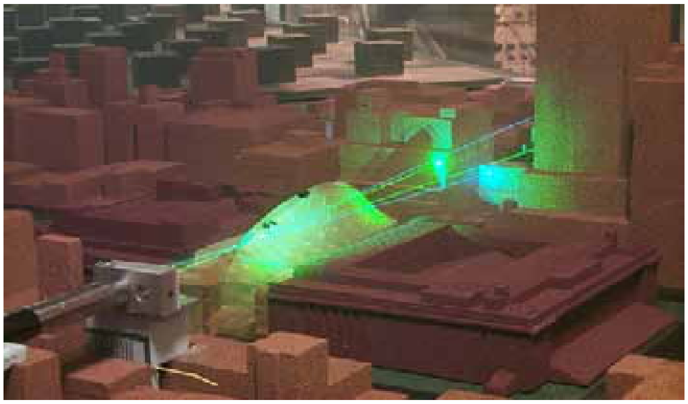

Figure 7: Laser velocimetry in the Meteorological Wind Tunnel at Colorado State University.

3 FORCE MEASUREMENTS

Figure 8: Aeroelastic model of the Titan V Launch Vehicle with the Mobile Service Tower backed away to the rear.

Even with the popularity of simpler and cheaper aerodynamic models (both the high-frequency force balance technique and the simultaneous pressure approach) to assess dynamic structural loads there is still the occasional unconventional project that requires a fuller exploration of the nonlinear relationship between the structural response and the forcing function via an aeroelastic study. Two interesting examples of this “Rolls Royce” analogue solution to the differential equations of motion are the Titan V Launch Vehicle (Figure 8) prior to lift-off and the architecturally decorative Houston Arches (Figure 9). The potential wind loads during the critical moments prior to the launch of any orbital vehicle may vary greatly with the arrival of an unexpected front or thunderstorm. In this study these load probabilities were assessed for a variety of meteorological conditions, positions of the Mobile Service Tower and fuel masses in the vehicle. The last condition provided a challenge for the aeroelastic model construction, particularly when there was no fuel load. The mass scaling parameters in this condition dictated that a very light thin shell be built. A variety of approaches were tried, including stereolithography and spun carbon fibre. With some experimentation a very thin payload shell was built using the finer limits of the stereolithography machine. Of course, the traditional issues of surface roughness and Reynolds Number for these circular cylinders came into play as well. A roughened, black surface in the payload area can be seen in Figure 8.

Figure 9: Aeroelastic model of the Galleria Arches in Houston, Texas.

A more Earth-bound, but equally interesting aeroelastic study was that of the Houston Galleria Arches in Figure 9. This public art spanning a major thoroughfare in commercial Houston had an interesting aerodynamically interactive response that required aeroelastic modeling. The aeroelastic models, fitted with very small accelerometers, responded to their own vortex shedding as well as the turbulence flowing off the upwind arch. Seven modes were effectively reproduced with this aeroelastic model. The final result was an elegant, full-scale, span of two 600 mm stainless steel tubes across the six-lane road in Houston, Texas.

The vast majority of buildings do not require the elegance of the aeroelastic approach to assess useful design wind loads, and so these projects may be evaluated using an aerodynamic model. In essence, this technique seeks to obtain the external loading (base-moment time series) on a given building shape via a light, stiff model in the wind tunnel, after which the dynamic response may be calculated in the time and/or frequency domain for any desired combination of mass, stiffness, damping ratio and wind speed. The structural engineer finds this methodology valuable since revised dynamic properties may be applied to the base-moment spectra or time-series data without returning to the wind tunnel, provided that the external building shape remains unchanged. This encourages a more economic and iterative design scenario for the structural engineer. Many attendees will be fully familiar with this approach, but those who wish to read more should read papers on the topic by Boggs (1992) and many others in the wind-engineering literature.

Figure 10: Simultaneous pressure data collection applied to a midrise condominium in Miami (510 taps).

However, what is relatively new in wind-tunnel testing is the availability of cheap pressure transducers. As a consequence, many laboratories can apply 500 to 1000 transducers to a pressure model and collect pressure time-series data, essentially simultaneously, over the entire building. To obtain the same base moment data as the force balance one needs to assign tributary areas, and moment arms to the axes for each of the taps – effectively a substantial accounting problem. From that point on the data-reduction is almost identical to the high-frequency force balance technique. The obvious advantage to this approach is only the pressure model needs to be built (Figure 10), and the lightweight balsawood (typically) force-balance model is not needed. There are, however, less obvious advantages. The high-frequency force balance theory is dependent upon linear mode shapes in bending, whereas in reality the building may have a mode shape with some curvature. This is even more of a concern for torsion, which should be approximately linear with height in the full scale but is constant with height on the force balance. Correction factors for these two criticisms of the high-frequency force balance are available in the literature, but the simultaneous pressure approach offers a

Figure 11: New Miami Air Traffic Control Tower with the old tower in the background.

way to accommodate these mode-shape issues via weighting the pressure data according to the true mode shapes of the full-scale structure.

For long, lowrise buildings (Figure 10) the high-frequency force balance will generate base moments contaminated by roof uplift pressures at the building extremities, well removed from the axis of rotation. The structural engineer does not want this impacting the horizontal loads on each floor. Those roof uplift forces are accommodated elsewhere in his design. For tall buildings (Figure 11 is an extreme example), with a relatively small footprint, this effect is imperceptible. The simultaneous pressure technique removes this problem since the experiment can be designed to take simultaneous data from wall taps only. This observation is fortuitous since it results in a useful and practical demarcation between times the high-frequency force balance is preferred over the simultaneous pressure approach. Tall building models tend to have a small internal volume, for pressure tubing, and so the force balance is preferred on that pragmatic basis. Conversely, the squat buildings do not lend themselves to the force balance and they have plenty of volume for tubing.

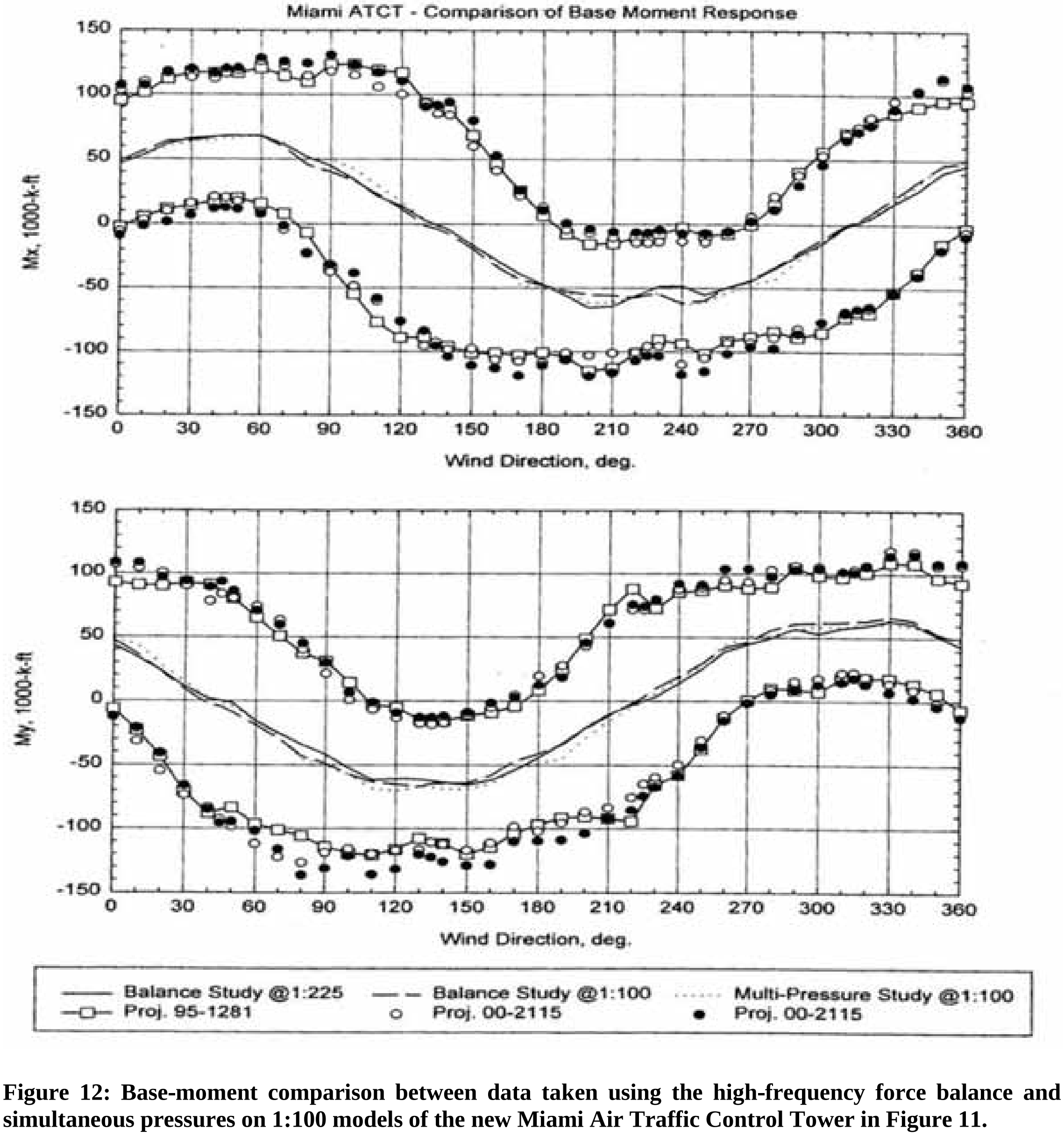

Figure 12: Base-moment comparison between data taken using the high-frequency force balance and simultaneous pressures on 1:100 models of the new Miami Air Traffic Control Tower in Figure 11.

The obvious question any structural engineer would ask is “do both techniques result in the same design loads?” Additionally, the wind engineer would like to know how many taps are needed to generate reliable design data. At CPP we have compared data collected using both the high-frequency force balance and simultaneous pressure for a variety of building shapes and surroundings. Those studies have suggested a relative insensitivity to the actual number of taps used – a sufficient number to capture the cladding data appears to be more than adequate for the integrated structural loads. The AWES Quality Assurance Manual (2001) also has some guidance of the number of taps needed. By way of example, Figure 12 shows the comparison of a 1:100 balsawood high-frequency force balance model of the new Miami Air Traffic Control Tower (ATCT) with a 1:100 pressure model of the same tower (note that 1000 k-ft = 1.356 MNm). This is a tall slender structure in an open upwind environment that would typically not be studied by the simultaneous pressure technique. However, it is useful in exploring how many taps are needed for such a simple prismatic shape. There were about 190 taps in the pressure model (all that could be placed inside the ATCT stem) for simultaneous pressure data collection. The relatively regular shape of the ATCT and lack of interfering structures resulted in a good data match even with these few number of taps. Similar comparisons with more complex buildings in more complex surroundings have produced comparable results with about 500 to 700 taps. Figure 12 also shows data for a 1:225 model of the same ATCT tested at an earlier time. An observant reader will notice that easterly flows generate somewhat different peak base moments (M_y) over a range of azimuths for the two 1:100 studies when compared to the 1:225 study. This is due to a 45-degree alteration in the understanding of the orientation of the existing ATCT upwind (Figure 11) between the 1:225 and 1:100 tests. This came about from better surrounding photographs in the second study when the orientation of the four legs of the existing ATCT became apparent.

Figure 13: Thirty-storey Florida condominium, with tall proximate neighbours, used to compare balsawood HFFB (shown) data with the simultaneous pressure technique.

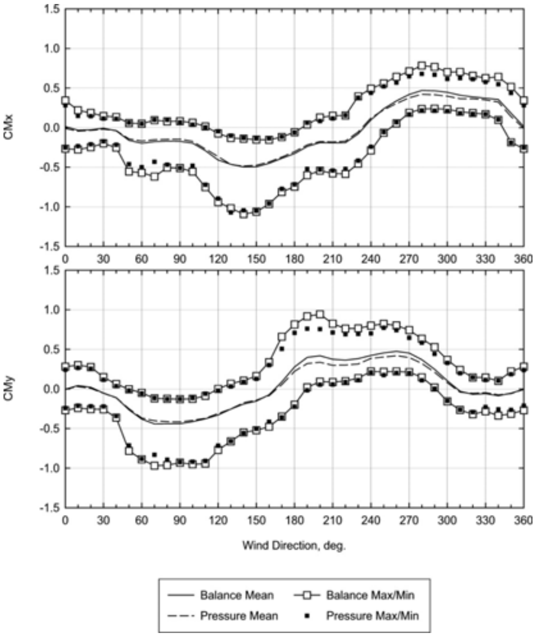

Figure 14: Mean and peak base moment coefficients about the x and y axes using both techniques.

Many comparisons have been made between these two approaches in more complex urban environments. Figure 13 shows an extreme example, with comparably tall buildings very close to the subject building. The mean and peak base moment coefficient data are compared in Figure 14 and the spectral responses are in Figure 15. In this case only 290 taps on the pressure model of the tower were used. The result is fair, but the southerly flow impacting the M_y base moment indicates an underestimation on the mean and peak base moments, probably due to the low number of taps used. Data like this have been used to suggest a lower bound to the number of taps needed. Interestingly, the fluctuating component of the load (distance between the mean and peak loads in Figure 14 and the sample spectra taken from the 200 degree load case in Figure 15) is in good agreement between the two techniques. These data, and other in-house studies, have led CPP to use between 400 and 700 taps in the typical simultaneous pressures study of a new midrise building in a complex cityscape.

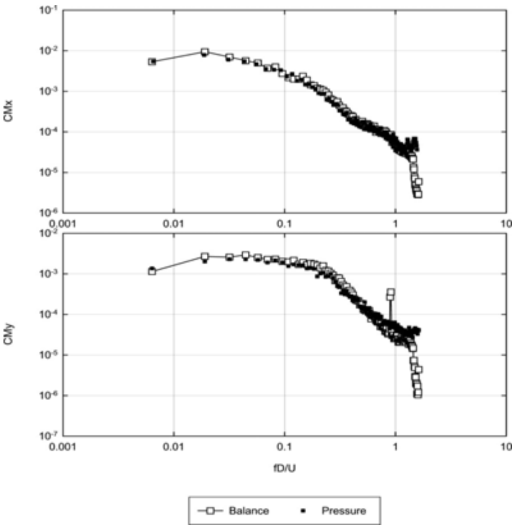

Figure 15: Mx and My spectra from the HFFB and 290-tap simultaneous pressures at 200 degrees.

4 NEW CLIENTS AND SERVICES

The arena of new developments in commercial wind engineering is influenced greatly by the needs of the client. One growing new area is forensic wind engineering with client driven needs as varied as glass or louvre failures in relatively modest winds to court cases concerning deaths resulting from wind-induced crane failures. The wind tunnel can produce crucial and convincing data for the legal fraternity in these areas of science and engineering.

Figure 16: Spoiler on the edge of the TTU Building in Lubbock, Texas (after Banks Sarkar Wu and Meroney, 2001).

Some clients wish to explore their own product research in the wind tunnel. Vortex fences and spoilers (Cochran Cermak and English, 1995; Cochran, 2004; Banks Sarkar Wu and Meroney, 2001) have been applied to critical-use buildings in hurricane areas of the United States. In a similar manner new designs for vertical and horizontal axis wind turbines (Figure 17) are more commonly being investigated on a consulting basis in the wind tunnel and in the field.

Figure 17: Full-scale wind turbine design is used to confirm model studies in the wind tunnel and initial CFD input.

Small-scale terrain models are often used to assess the best approach conditions for a building sited in, or adjacent to, complex terrain. Those measured profile data are then used to define the appropriate profile upwind of the subject-building turntable at, say, 1:400 or 1:500. For these small-scale studies Meroney (1980) suggested a model scale limit of about 1:6000 while Bowen (2003) suggests about 1:5000. The latter discussion lists a thought-provoking array of shortcomings associated with these small-scale physical terrain models. Obviously as the scale reduces the more significant turbulence wavelengths fall prey to viscous dissipation. Is this a serious concern for the designer of the experiment? Is the omission of the Coriolis-induced Ekman spiral a shortcoming of consequence as the modeled area increases? When is the loss of Coriolis forces acceptable in complex terrain flows? When is ignoring possible full-scale variation in atmospheric stability diminishing the value of the physical model study? Strong winds, perhaps? When is the loss of gravity waves and the consequent asymmetry on either side of a mountain range, created by stability in the atmosphere, acceptable in the modeling process? The use of a stepped model is commonly used to replicate, or perhaps artificially exaggerate, the true surface roughness at these small scales. This may be reasonable for gross profile assessment as in Figure 18, but what if data closer to the surface are needed? Should the steps be smoothed out and the Reynolds Number mismatch of several orders of magnitude be accepted? Large-area flows like these might now be better modeled using nested, mesoscale, numerical models that have their origins in the field of atmospheric science. CPP is currently comparing profile wind data from 1:4000 terrain models with those generated numerically. The numerical runs may be performed with neutral stability and no Coriolis forces to replicate the conditions in the wind tunnel (for initial comparative purposes) and then, if satisfactory, run again with these pieces of physics turned on for a truer picture of flows over complex terrain. It may be that once this approach is validated the use of small-scale physical models may be used far less. Perhaps this will be the first practical use of Computational Wind Engineering (CWE), rather than the dubious solutions to flows around buildings in an urban environment - with all the inherent turbulence modeling concerns.

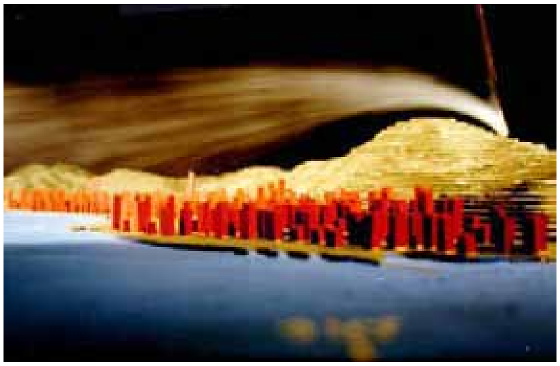

Figure 18: Separated flow over Central caused by southerly winds over Victoria Peak in Hong Kong, China (1:4000).

Another trend in consulting wind engineering, which seems likely to continue, is the combination of complex architecture (Figure 19) and reduced real costs of a typical wind-tunnel study. This has caused many mid to lowrise buildings to be tested for cladding and structural loads. It is not uncommon for buildings in the eight to twelve-storey range to be put in the wind tunnel. Even a few exotic, expensive (20 M$), single-storey homes have been tested in the wind tunnel, although this is not a common client. As more condominium developers realize the benefits for their design this trend will continue, particularly in hurricane prone areas. For residential towers some developers actually use the pressure model and a flow-visualization DVD of the testing in their display unit as a selling point, emphasized to potential purchasers.

Consulting in wind engineering will occasionally expose you to a structural engineering client who appears to be somewhat out of his/her depth as the wind-tunnel study evolves. They really need to be helped, but it can be painful! Clues might include being asked to spell “eigenvalue” or “eigenvector” to him/her over the telephone so that he/she may look it up in the STAAD or ETABs manual. Perhaps when you are asked to explain what “torsion” is on a 50-storey building you should be concerned. If you are asked how much it would "cost" to reduce the loads prior to issuing the Final Report you suspect this is an ethically challenged client. On the rare occasion that the structural loads are larger that the relevant code the engineer may suggest filing the wind-tunnel data and just "going with the code". Panic! How do we subtly ease them in the right direction? At what point may our engineering ethics cause us to consider stronger action? If so, what? The peer-review process will eventually "educate" most of these ethically challenged clients, but not all of them. One of mine actually ended up with prison time when he colluded with a building inspector to ignore a "minor problem".

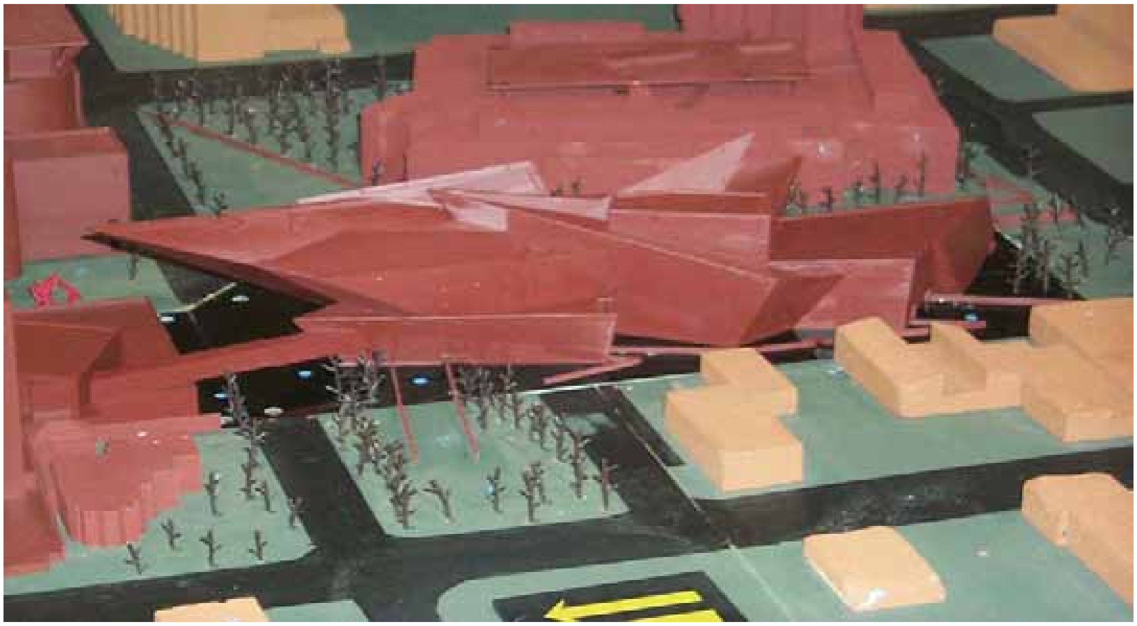

Figure 19: Complex geometries, such the Denver Art Museum, are immediate candidates for a wind-tunnel study. However, even more conventional midrise structures, such as shown in Figures 10 and 13, are routinely tested for the economic benefits that acrue when compared to a code-based design.

5 WIND ENERGY

Over the last few years the most noticeable growth area in consulting wind engineering in the USA has been the huge growth in wind-energy projects. In most of the states immediately east of the Rocky Mountains the wind resource is huge (Figure 20). The landowners obtain royalties from the power companies and they can still use the land for traditional grazing and farming. With the arrival of quality, well-designed, Danish (clearly world leaders in wind energy), horizontal-axis turbines the price of power form this source is genuinely competitive. A gas-fired power station generates electricity at slightly over four US cents per kW-h, while wind energy prices out at slightly less than four US cents per kW-h (The Coloradoan, 26 January 2003). In the United States about nine percent of the electric power comes from renewable sources, and most of that is hydropower (about seven percent). Thus, the growth of wind turbine installation has been, and is, exploding. The old complaint of bird deaths from the moving blades is largely a thing of the past. The modern, more efficient blades rotate more slowly and the birds seem to be able to see them. Worldwide wind power capacity has grown by *fifty percent* from 2000 to 2001 alone (Solar Today, November 2002), while in the United States wind-energy capacity has grown annually at an average 24.5 percent over the five years from 1998 to 2002 (Solar Today, January 2004). These growths show no immediate sign of abating. As wind-engineers we can assist in the siting of the machines relative to the terrain, help in the design of new turbines, and provide short-term forecasts of wind-power generation for the utilities to aid in their management of more traditionally fueled power sources.

Figure 20: The strong growth of wind energy power generation is an area for future development in consulting wind engineering. The site shown here is on the Colorado and Wyoming border.

6 HIGHRISE BUILDINGS

The next step in improving our knowledge of highrise building response is to convince the developer and/or owner to instrument (accelerometers, pressure transducers, strain gauges etc) their buildings for research purposes. This already happens routinely in earthquake areas for building motion on the west coast of the United States. However, only a handful of buildings on the US hurricane coast have wind-engineering-oriented instrumentation installed. Unfortunately, building owners are reluctant to have quantitative data about the performance of their tall office or residential building be commonly known. Despite this hurdle, more instrumented full-scale data is likely to be available in the near future.

One glaring research need is a better codification of torsional loads on buildings (M_z). The newer wind-loading codes make some attempt at this, but the end result often bears little resemblance to reality and is frequently unconservative. With modern, complex architecture it is now more common to find the centre of stiffness considerably displaced from the centre of mass (e.g. elevator cores near the end of a building, not the centre) and when this is combined with asymmetrical flows, caused by neighbouring buildings (Figure 21), torsion may be a major concern. Torsion can also be more significant for curved buildings than their rectilinear counterparts. One observation is that midrise condominiums with a “banana-shaped” floor plan frequently have substantial torsional loads. Additionally they tend to occur close to the wind direction that maximizes the two horizontal bending moments (M_x and M_y). In condominium design architectural considerations often dictate that peripheral shear walls are not possible. Thus, stiffness about the vertical axis may be low and this will aggravate the torsional response with a susceptible building shape. This condition may result in the fundamental modal response of the building not being in bending, but being dominated by torsion about the vertical axis. This can produce peak torsional base moments (M_z) with magnitudes of thirty to forty percent of the peak base overturning bending moment (M_x or M_y). A structural engineer using a code-based design would have no reliable knowledge of this action on his/her design.

Figure 21: The oval building in the centre generated large torsional loads on the rectangular building to the right by partially shielding the dominant winds on its wide face. Fortunately it was tested with and without the oval building in place during a previous study and was designed to accommodate the torsional loads. How many buildings are not assessed in this manner?

7 OPERABLE FACADES AND GREEN BUILDINGS

Figure 22: The Genzyme Headquarters in Boston, Massachusetts, was analyzed for cladding pressures when selected critical windows were assumed open during a design storm.

It is fairly common for wind-engineering laboratories to account for broken or open windows by using a series of simultaneous pressure differences across a communicable internal space, where one pressure represents the transmitted internal pressure generated at what would be the opening in the full-scale building (Cochran and Peterka, 2001). This approach works quite well, but it is somewhat conservative. It assumes that the broken window occurs at the worst location enclosing a given building volume when the wind blows from the worst wind direction in the design storm. This string of unlikely events suggests that a reduced return period could be applied to the open-window design pressures. A recent development is to assign a rational probability analysis to this process, so that the largest pressure difference is not used. Some lesser peak pressure difference serves better for a riskconsistent design. The building in Figure 22 has a computer-controlled façade (actuators at the operable windows) to aid in the natural ventilation of the internal space. The façade had to be designed to account for the unexpected case of the sudden arrival of a thunderstorm front at or near the design wind speed. In that circumstance some severe external pressures could be transmitted to the internal space if windows were unable to close in time or were subject to a power failure. An example of the real time differencing used in this green-building study is given in Figure 23. Here a portion of a pair of time series data that resulted in the largest pressure difference on one floor is shown (taps 423 and 611) and the largest difference was about 3.3 kPa. This type of maximum-difference search analysis is performed for all the tap-pair combinations relevant to a given internal space for all 36 wind directions.

A similar question has arisen in recent times with the advent of 300-m residential buildings. At such high elevations tenants opening their balcony doors during a strong wind event could differentially load the lightweight partition walls between the units substantially. In the typical shorter buildings of the past this was a small pressure difference and it was rarely even considered. Some research is needed to give guidance on this topic to the structural engineer and architect. However in the interim, using measured pressure data across two building models and judging the likelihood of tenants simultaneously opening doors during a design storm, two independent commercial laboratories advised values of 2.4 kPa and 2.0 kPa for two residential buildings of 300 m and 270 m height, respectively, for this scenario. Even so, some additional work in this area is needed.

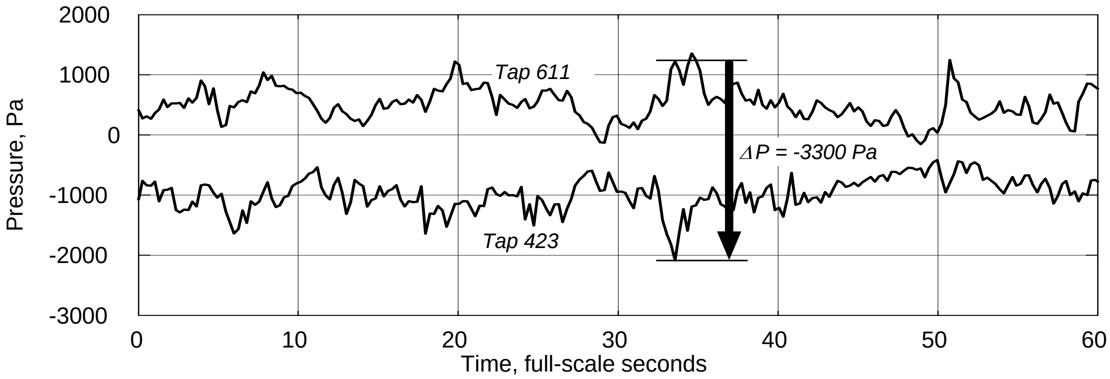

Figure 23: A typical example of simultaneous time-series pressure differences that were searched for maxima by wind direction and position on the curtainwall (after Cochran and Peterka, 2001).

8 COMPUTATIONAL WIND ENGINEERING

Lastly, the most obvious future development in commercial wind engineering will be the maturation of Computation Wind Engineering (CWE). There is still much research to be done on turbulence models, solution algorithms, domain generation and gross computing power before structural and cladding loads are routinely performed on a computer, but I expect to see it in my professional lifetime. Probably the most difficult will be the generation of peak cladding pressures from the turbulent Navier-Stokes equations. The truly frightening observation is that people, without much understanding of the wind or flow physics, are taking commercial programs, designed for low-turbulence internal flows, and they are applying them to external, highly-turbulent winds around buildings (Cochran, 2002). In reviewing some recent journal papers there are examples of CFD-generated flows around lone, tall, rectangular buildings that did not even show the elementary phenomenon of downwash. The authors were either unaware or did not care about this fundamental shortcoming. It is examples such as this that lead researchers to refer to CFD as “Colourful Flow Drawings”.

The lack of validation (as was done in the early years of wind-tunnel modeling) could easily mislead a well intentioned structural engineer into thinking his CFD package is generating real design wind loads. It is the duty of commercial and research wind-engineers to take the lead in CWE so that it is used where the technology is appropriate. We have a far better understanding of the turbulent flow physics. The three international CWE conferences were a start, but we need to be more forceful in the broader engineering arena. Even at this early stage there may be realms where CWE can positively contribute. For example, large-area meteorological flows over complex terrain (nested grids used in codes developed by atmospheric scientists, such as ARPS or RAMS), thermally driven flows associated with internal atrium fires and certain smaller-scale dispersion studies seem to be the most likely first steps. I used to think that pedestrian-wind studies might also be a good candidate too. However, people far more knowledgeable than me about the intricacies of CWE tell me that surface-adjacent flows are the most difficult to calculate correctly. In fact, this area of the flow is often the boundary condition used to tweak the desired answers. Thus, CWE is the way of the future, but wind engineers need to take the lead among other consultants to ensure that poorly or non-validated data are not taken as gospel by designers less familiar with the intricacies of the natural wind.

9 REFERENCES

Australasian Wind Engineering Society, “Quality Assurance Manual for Wind Engineering Studies of Buildings (AWES-QAM-1-2001)”, 33 pages, 2001.

Banks, D, Sarkar, P.P., Wu, F. and Meroney, R.N., “A Device to Mitigate Vortex Induced Rooftop Suction”, Proceedings of the Ninth Americas Conference on Wind Engineering, Clemson University, Clemson, South Carolina, 10 pages, 2001.

Boggs, D.W., “Validation of the Aerodynamic Model Method”, Journal of Wind Engineering and Industrial Aerodynamics, Volume 41-44, pages 1011 to 1022, 1992.

Bowen, A.J., “Modelling of Strong Wind Flows Over Complex Terrain at Small Geometric Scales”, Journal of Wind Engineering and Industrial Aerodynamics (under review).

Cermak, J.E., “Wind-Tunnel Testing for Wind-Engineering Applications”, Keynote Lecture for the Eightieth Anniversary Celebration of the National Central University at Chungli, Taiwan, June 1995.

Cochran. L.S., “Wind Effects on Lowrise Buildings”, Proceedings of the Second National Conference on Wind Engineering, Commemorative Volume to Honour Professor Prem Krishna, Indian Society for Wind Engineering, Volume 1, pages 79-99, 2004.

Cochran, L.S., “Wind Analysis Evolves”, Letters to the Editor, Engineering News Record, McGraw Hill Construction, page 5, Issue 30 September 2002.

Cochran, L.S. and Peterka, J.A., "On Breached Building Envelopes and Increased Internal Pressures", Proceedings of the ICBEST-01 Conference, Ottawa, Canada, pages 83-87, June 2001.

Cochran, L.S., "Wind Engineering as Related to Tropical Cyclones", Storms Book - Chapter 14, edited by Roger Pielke Sr. and Roger Pielke Jr., Routledge Press, London, pages 242-258, 2000.

Cochran, L.S., Cermak, J.E. and English, E.C., "Load Reduction by Modifying the Roof Corner Vortex", Proceedings of the Ninth International Conference on Wind Engineering, New Delhi, India, pages 1091 to 1102, 1995.

Irwin, H.P.A.H. and Kochanski, W.W., "Measurement of Structural Wind Loads Using the High Frequency Pressure Integration Method", Proceedings of the XIII ASCE Structural Congress, Boston, 1995.

Meroney, R.N., "Wind-Tunnel Simulation of the Flow Over Hills and Complex Terrain", Journal of Wind Engineering and Industrial Aerodynamics, Volume 5, pages 297-321, 1980.

Sandborn, V.A., "Class Notes for Experimental Methods in Fluid Mechanics", Department of Civil Engineering, Colorado State University, Fourth Edition, 1981.

Sandborn, V.A., "Resistance Temperature Transducers", Metrology Press, Fort Collins, 1972.

Schubauer, G.B. and Klebanoff, P.S., "Theory and Application of Hot Wire Instruments in the Investigation of Turbulent Boundary Layers", N.A.C.A. Wartime Report, Advance Confidential Report 5K27 W86, 1946.