Commercial Wind Engineering: New Developments, Queries, Blunders and the Future

Leighton Cochran

Introduction:

The primary intent of this invited presentation at the 10th AWES Workshop is to discuss new developments in 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.

Developments:

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 prior to lift-off and the architecturally decorative Houston Arches.

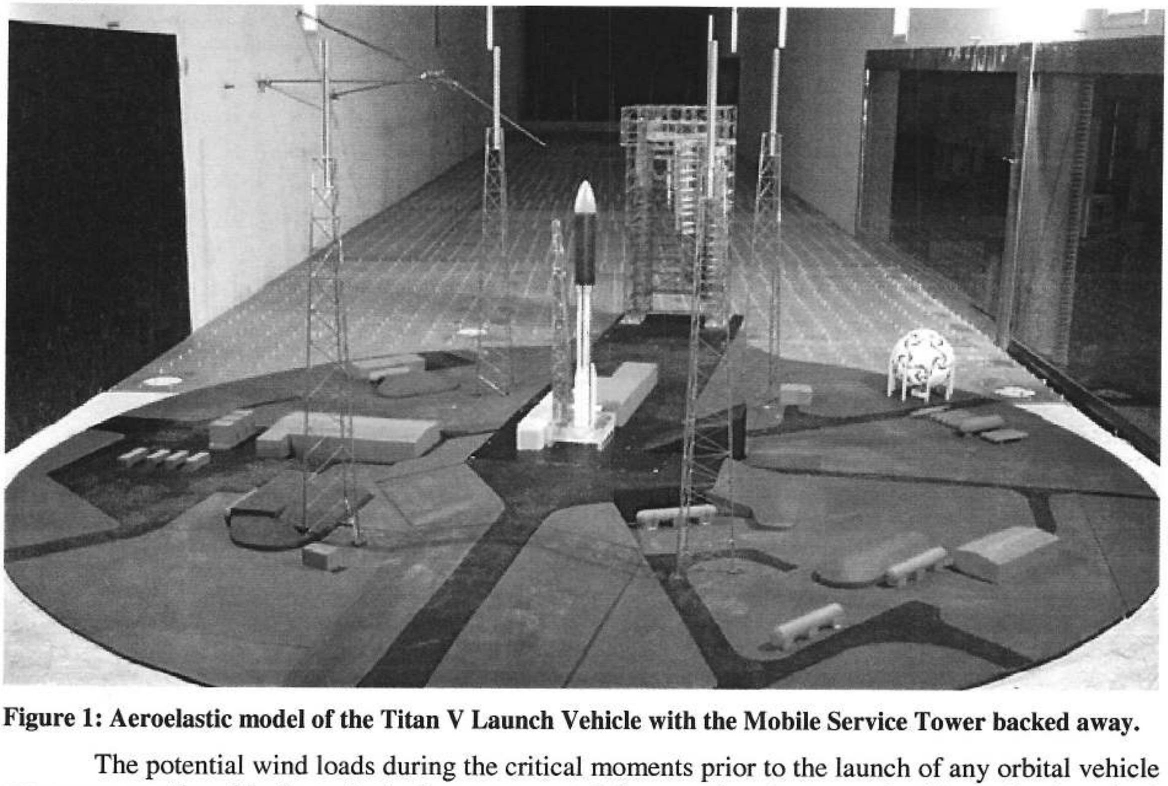

Figure 1: Aeroelastic model of the Titan V Launch Vehicle with the Mobile Service Tower backed away.

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 1.

A more Earth-bound, but equally interesting aeroelastic study was that of the Houston Galleria Arches. This public art spanning a major thoroughfare in commercial Houston had an interesting aerodynamically interactive response that required aeroelastic modeling. The aeroelastic models (Figure 2), 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.

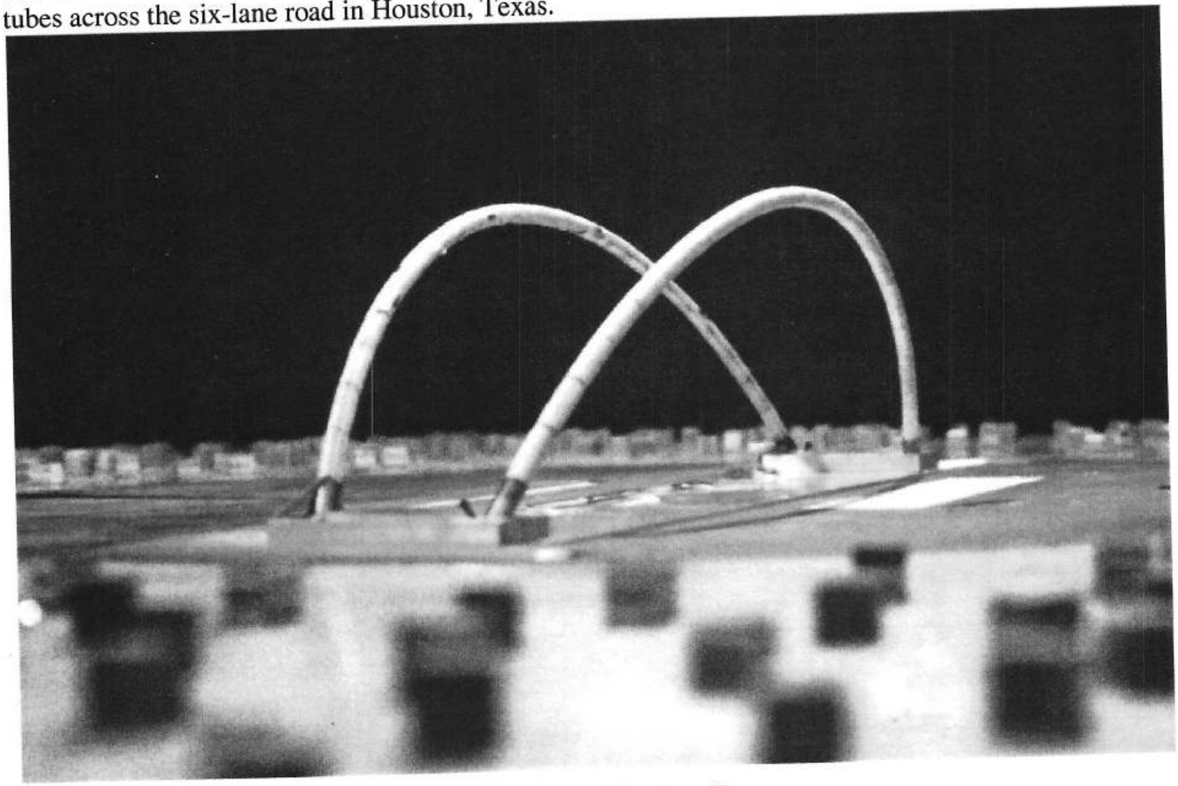

Figure 2: Aeroelastic model of the Galleria Arches in Houston, Texas.

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 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.

However, what is relatively new in wind engineering 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, 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 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 3) 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, 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.

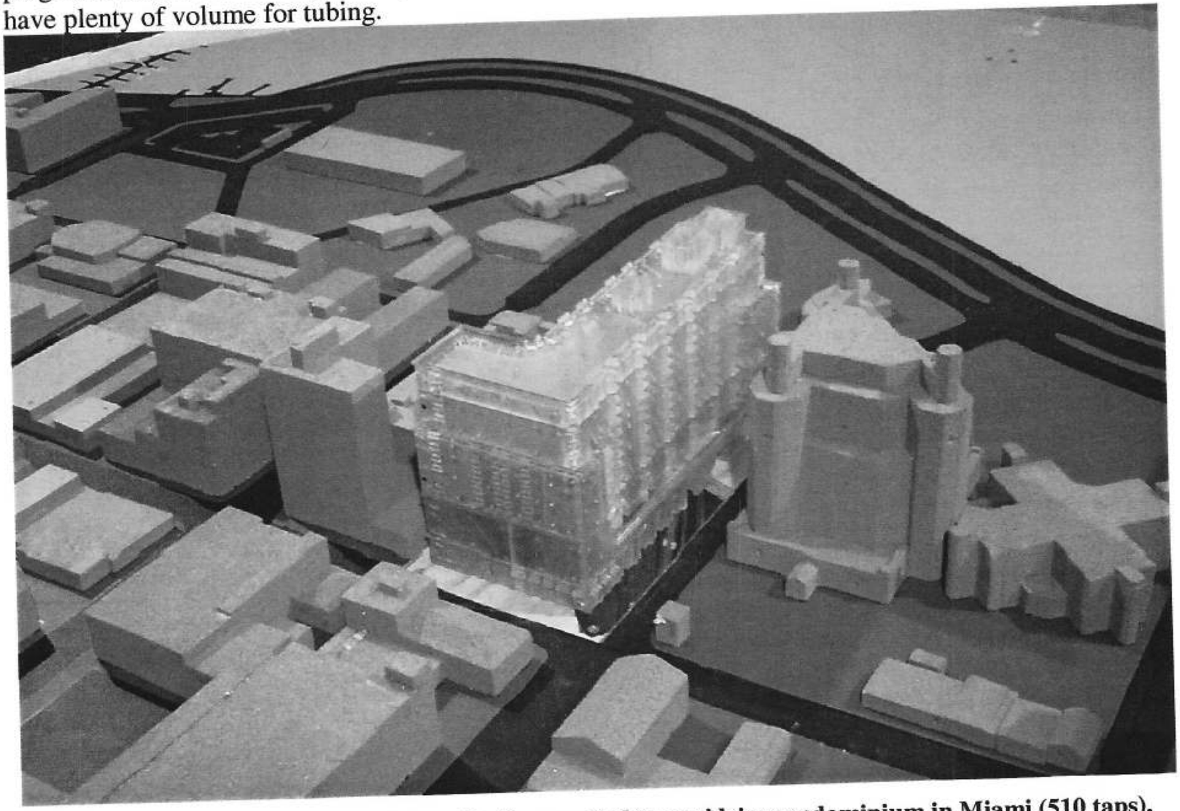

Figure 3: Simultaneous pressure data collection applied to a midrise condominium in Miami (510 taps).

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. 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 adequate for the integrated structural loads. The new AWES Quality Assurance Manual also has some guidance of the number of taps needed. By way of example, Figure 4 shows the comparison of a 1:100 balsawood high-frequency force balance model of the new Miami Air Traffic Control Tower with a 1:100 pressure model of the same tower. There were about 190 taps in the pressure model 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 4 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. This is due to a 45-degree alteration in the understanding of the orientation of the existing ATCT upwind between the 1:225 and 1:100 tests. This came about from better surrounding photographs in the second study when the four legs of the existing ATCT became apparent.

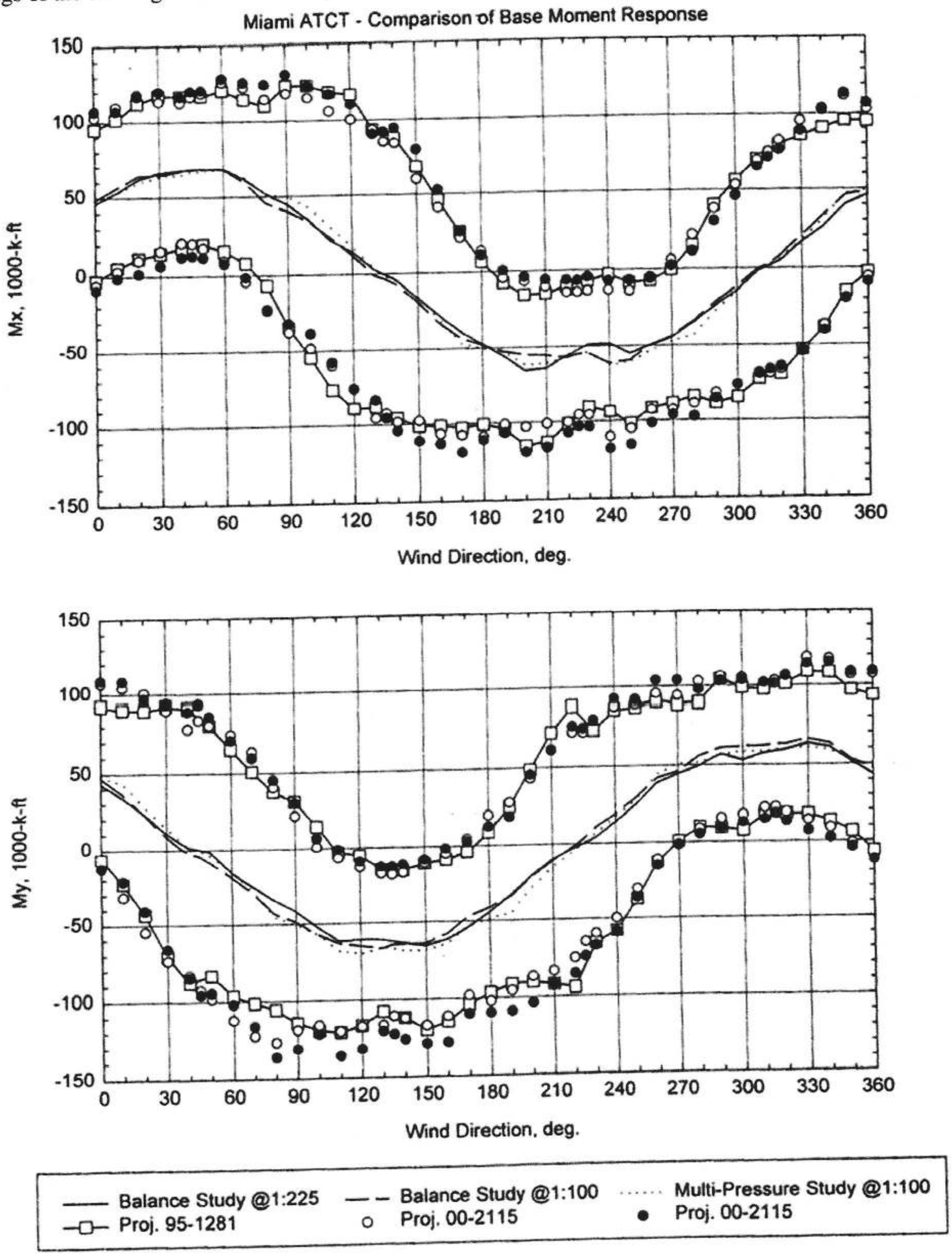

Figure 4: Base-moment comparison between data taken using the high-frequency force balance and simultaneous pressures on 1:100 models of the new Miami Air Traffic Control Tower.

Laser velocimetry has been used routinely in fluid mechanics for at least a decade, but it is now starting to appear in the commercial side of wind engineering to help clients with particular problems. Figure 5 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. With a good understanding of the winds around the lattice and knowledge of the member shapes the structural wind loads can be better assessed for the structural engineer.

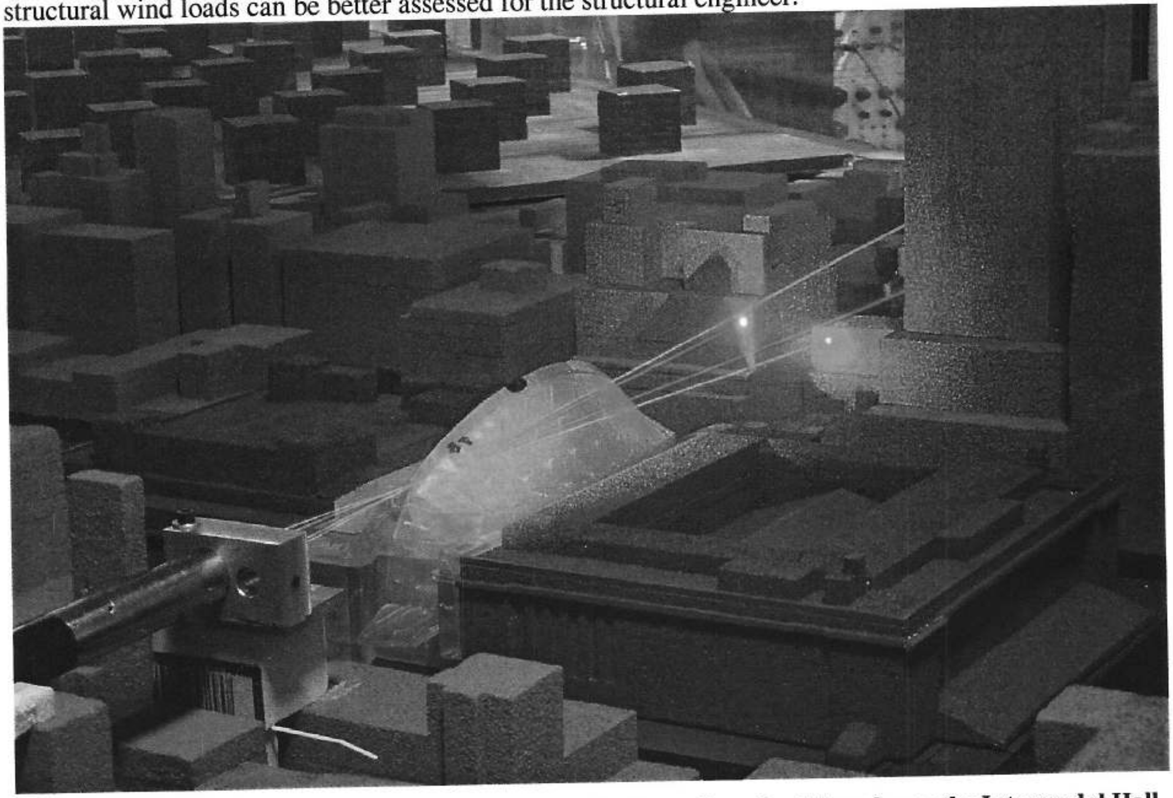

Figure 5: Establishing the velocities around a curved lattice ends and solid roof over the Intermodal Hall.

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 failures in modest winds to court cases over deaths resulting from wind-induced crane failures. The wind tunnel can produce crucial and convincing data for the legal fraternity in areas of science and engineering.

Some clients wish to explore their own product research in the wind tunnel. Vortex fences and spoilers (Cochran et al. 1995 and Banks et al. 2001) have been applied to critical use buildings in hurricane areas of the United States. New designs for vertical and horizontal axis wind turbines are more commonly being investigated on a consulting basis in the wind tunnel and in the field.

Queries:

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 6, 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 6: Separated southerly flow over Central caused by Victoria Peak in Hong Kong (1:4000).

In wind engineering we have a rather loose use of terminology that may confuse outsiders. For example, it is common to use the term "rms" when we really mean "standard deviation", or their squared equivalents ("mean square" and "variance"). The mean square of a stationary record equals the average of the squared data values – thus, it includes the mean in the calculation. However, the variance (and so the standard deviation) has the mean value subtracted. Thus, a record with a non-zero mean has an rms different from the standard deviation. Only if the mean is zero, such as top-floor acceleration, are these values the same (Bendat and Piersol, 2000). Some may regard this as pedantic, but should we make an effort to move towards more precise and rigorous terminology?

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" to him over the telephone so that he/she may look it up in the STAAD 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".

The Council on Tall Buildings and Urban Habitat announces the heights of the tallest buildings in the world with a curious collection of definitions. This often serves to confuse the public and the media. Figure 7 shows some of the tallest buildings in the world (tragically two are now gone) and the Petronas Towers are said to be the current tallest since their spires (architectural features) are higher than the roof of Sears Tower, whose antennae are not regarded as part of the architectural intent. Sears Tower has higher occupied floors, higher roof and, I believe, higher spires. Perhaps we should compare apples with apples? Curiously a recent article in The Australian (23 August 2002) presented a comparative drawing with distorted building heights in order to avoid this visual contradiction.

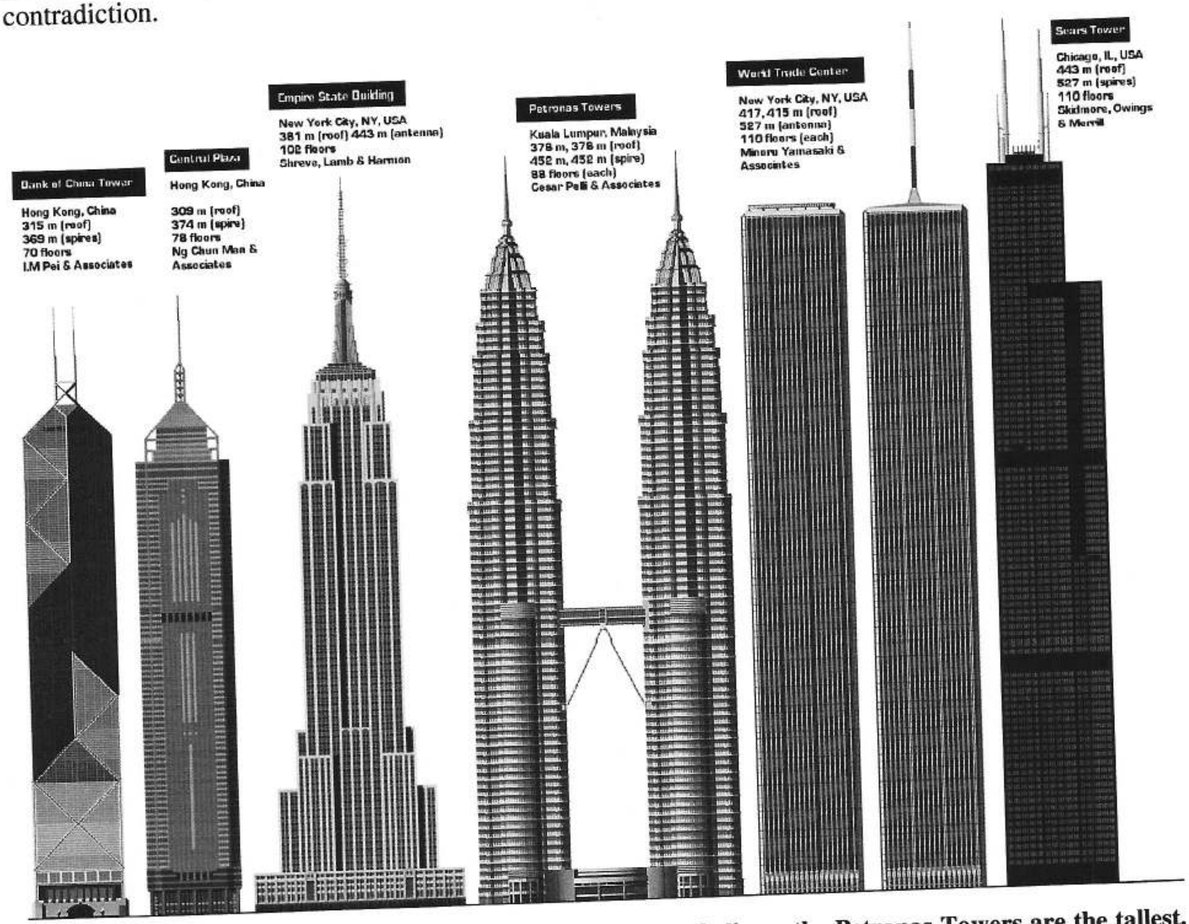

Figure 7: The Council on Tall Buildings and Urban Habitat believes the Petronas Towers are the tallest. Do you?

Blunders:

Here is the cathartic part. Engineers of all disciplines can gain much from the open discussion of minor and major errors, but we tend to keep our blunders close to the chest. One may call it ego or embarrassment, but in either case it seems prudent for more conversation to occur. Bill LeMessurier's recent and frank plenary lecture at an ASCE Structures Congress about his post-construction concerns over quartering-wind loads on the Citicorp Building in New York City was a rare example of the value of discussing the human side of engineering. He talked about how he realized that this landmark structure had a fundamental weakness when the wind was not perpendicular to a face, and then he went on to describe the urgent retrofit that occurred as a severe hurricane rapidly approached New York City. Inspired by Bill's lecture let us discuss some less dramatic, but still interesting, mistakes that we can all learn from. Perhaps the attendees at the AWES workshop may have a few stories of their own to contribute.

When the wave of construction started in Southeast Asia during the early 1990s many new projects were coming from Bangkok, Thailand. In an effort to better understand the wind records available for Bangkok it seemed reasonable to look at the historic tracks of typhoons over Thailand. With the help of an enthusiastic graduate student in the Atmospheric Science Department at the university dozens of typhoon tracks were plotted over Thailand. It did seem curious that the storms appeared gain in intensity as they passed over southern Thailand. Perhaps they gained thermal energy from all the warm water in the rice paddies in southern Thailand? This was a desperate rationalization! Some further investigation revealed that the wrong sign had been applied to the longitude in the data base search and the data plotted over Thailand were actually histories of hurricane approaching Hawaii. Figure 8 illustrates the impact of using a database incorrectly.

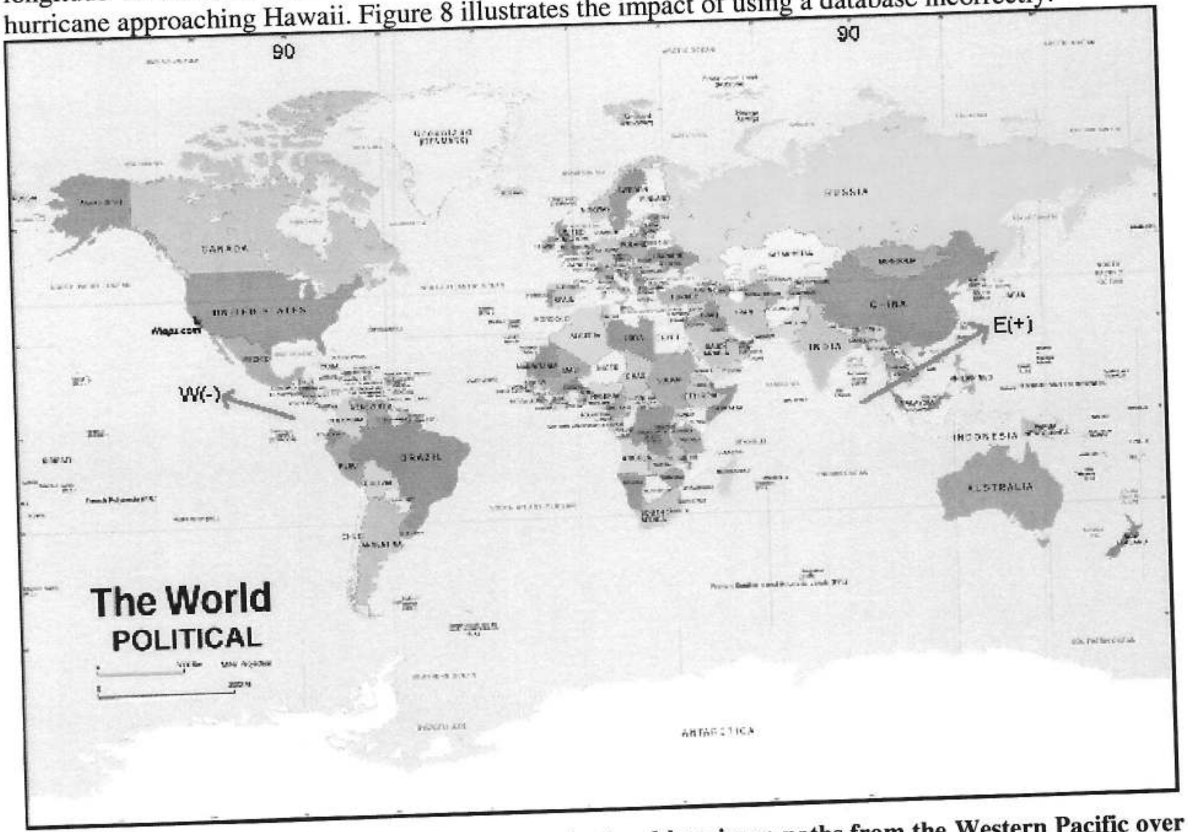

Figure 8: A simple sign error in a database search placed hurricane paths from the Western Pacific over Thailand. This generated typhoons that gained strength over land. Curious?

All wind-engineering laboratories have quality assurance programs in place – to varying degrees of formality. Not to do so would be litigious suicide. A key element is the role of the project manager in insuring technical and engineering correctness during the whole project; from the time shop drawings of the subject building are developed to confirming the reasonableness of the data presented in the Final Report. Imagine the embarrassment when my client informed me that we had modeled the plan curvature on the sides of a 420-m building as a radius, instead if a diameter. Since such a tall structure has loads dominated by vortex shedding, which is influenced greatly by the curvature of the four sides, the whole study was effectively useless. Fortunately, the client was good humored saw some value, in a research sense, in the parametric study of two radii on an exposed tall building. However, the whole model had to be rebuilt and retested in a very short time frame at considerable in-house expense. As part of my role as project manager I should have picked up on this major modeling error. Having the client point it out was not a pleasant experience, but ultimately it was good not have this error go any further in the design process. The need for a commercial wind-engineering laboratory to have an active quality assurance program ranges from the tangible connection of instrumentation calibration to national and international standards (micro manometers for pressure transducers, traceable masses for force-balance calibration, quality calibration gasses for dispersion studies, etc.) to the intangible knowledge base of what is reasonable; all held in the heads of the company partners. The latter is hard to quantify, but in part the client is paying for that wealth of experience in every project studied by an established laboratory.

An old mentor of mine used to say that the wonderful thing about flow visualization is that "you can see whatever you want to see". Whilst this is a tad cynical it does point out the susceptibility of flow visualization to human interpretation and perhaps the mechanism used to observe flow in the wind tunnel. In a variable and, perhaps confused, flow regime one person may see separated flow while another may perceive a vortex dominating the physics. Perhaps we make some flow visualization errors due to our instruments as well. The low-velocity flow from a smoke generator may influence what we wish to see. If a wand with titanium-dioxide smoke is used the presence of the wand may alter the formation of the tiny vortex we wish to see. Dabbing the surface of interest with the liquid titanium tetrachloride often yields a better result. Figure 9 dramatically illustrates the effect of the wand on a flow investigation. This was one of six photographs taken of the same phenomenon and only this one shot showed the shedding off the wand. Whilst not a major "blunder", perhaps we need to give more thought to our flow visualization techniques.

Figure 9: Flow shedding off the wand many influence the flow phonomenon we wish to observe on this Florida condominium. How much does the act of observing impact what we see?

Future:

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. 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 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) and this growth shows 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.

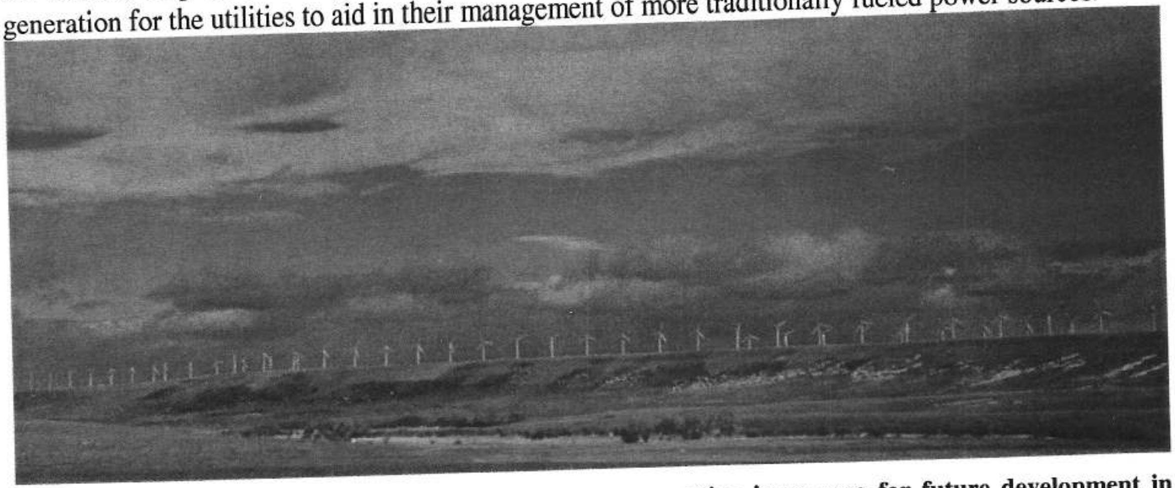

Figure 10: The strong growth of wind energy power generation is an area for future development in consulting wind engineering. The site shown here is on the Colorado and Wyoming border.

Another trend in consulting wind engineering, which seems likely to continue, is the combination of complex architecture 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 ten to twenty-storey range to be put in the wind tunnel. As more developers realize the benefits for their design this trend will continue, particularly in hurricane prone areas. For residential buildings some owners actually use the pressure model and a flow-visualization video of the testing in their display unit as a selling point emphasized to potential purchasers.

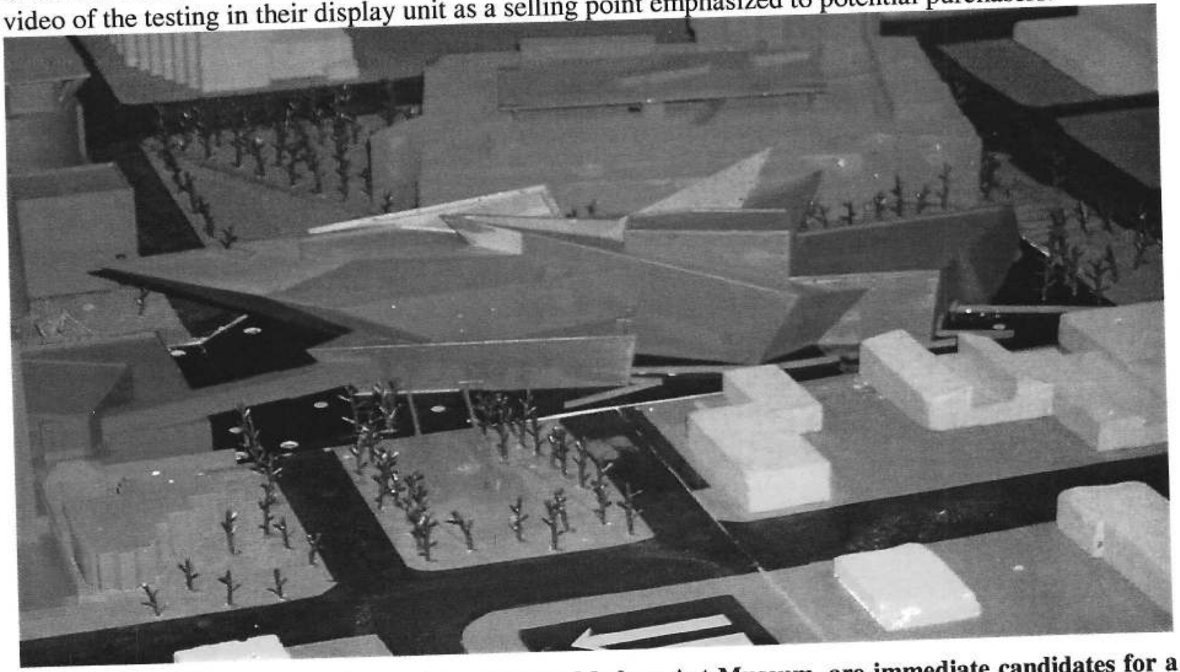

Figure 11: Complex geometries, such the Denver Modern Art Museum, are immediate candidates for a wind-tunnel study. However, even more conventional midrise structures, such as shown in Figures 3 and 13, are routinely tested for the economic benefits that acrue when compared to a code-based design.

The next step in improving our knowledge of building response is to convince the developer to instrument (accelerometers, pressure transducers, strain gauges etc) their buildings for research purposes. This already happens routinely in earthquake areas for building motion. 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 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. 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 12), torsion may be a major concern. In condominium design architectural considerations often dictate that peripheral shear walls are not possible, and so stiffness about the vertical axis may be low. This condition often results 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 with magnitudes of thirty to forty percent of the peak base overturning bending moment. A structural engineer using a code-based design would have no knowledge of this action on his/her design.

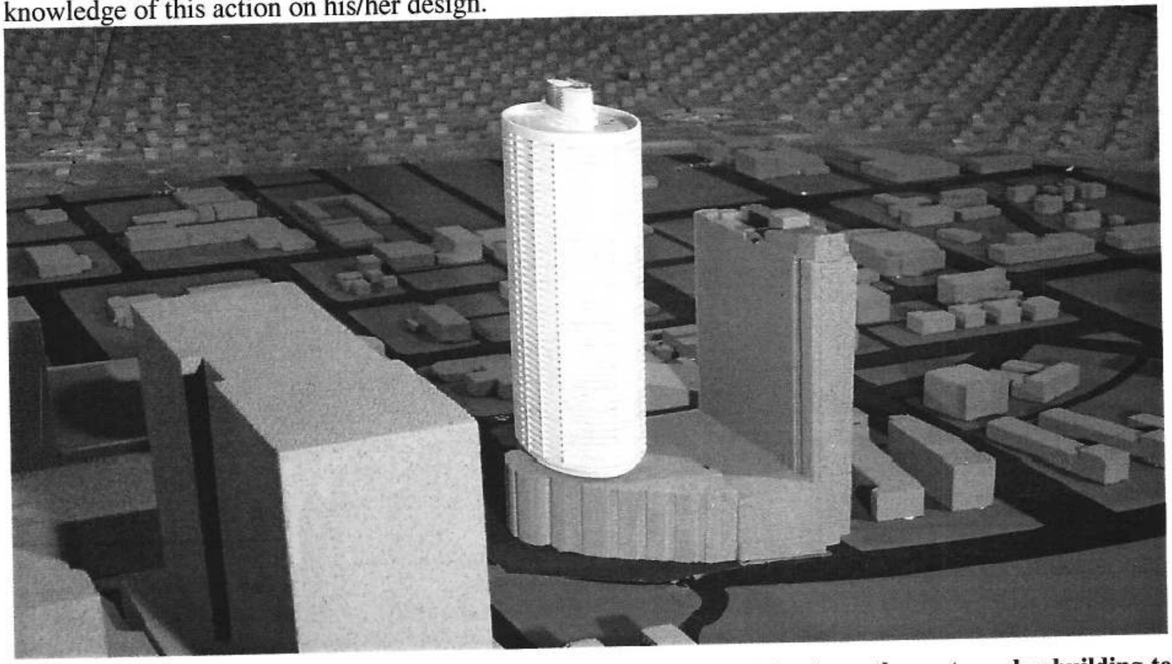

Figure 12: The oval building in the centre generated large torsional loads on the rectangular building to the right by partially shielding the dominant winds on its wide face. Fortunately it was tested with and without the oval building in place during a previous study and designed to take the torsional loads. How many buildings are not assessed in this manner?

On a less technical front the public is exposed to a variety of wind speed claims after a cyclone or hurricane. Some are a product of human nature and the desire to exaggerate the numbers for dramatic or shock-value reasons, and others come from the plethora of wind speed definitions. Atmospheric scientists work with different averaging times ("sustained winds" versus a wind engineer's "peak gust") and positions in the atmosphere ("surface winds", 10-m winds and winds at elevation). The media reports hourly winds, sustained winds, gust speeds and even fastest mile speeds (older US anemometers) at various positions in the profile interchangeably and so wind speed myths evolve in the public psyche. For example, maximum destructive winds caused by Hurricane Andrew (1992) in Miami were reported ranging from 130 mph (58 m/s) to well over 200 mph (89 m/s). In the future perhaps we will close in on more consistent terminology. Then we will only have to deal with the overzealous reporter who just wants a big number!

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 may be somewhat conservative since 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. A useful future development would be to assign a rational probability analysis to this process, so that the largest pressure difference is not used. Some lesser peak pressure difference would probably serve better for a risk-consistent design. Any volunteers?

Figure 13: The Genzyme Headquarters in Boston, Massachusetts, was analyzed for cladding pressures when selected critical windows were assumed open during a design storm.

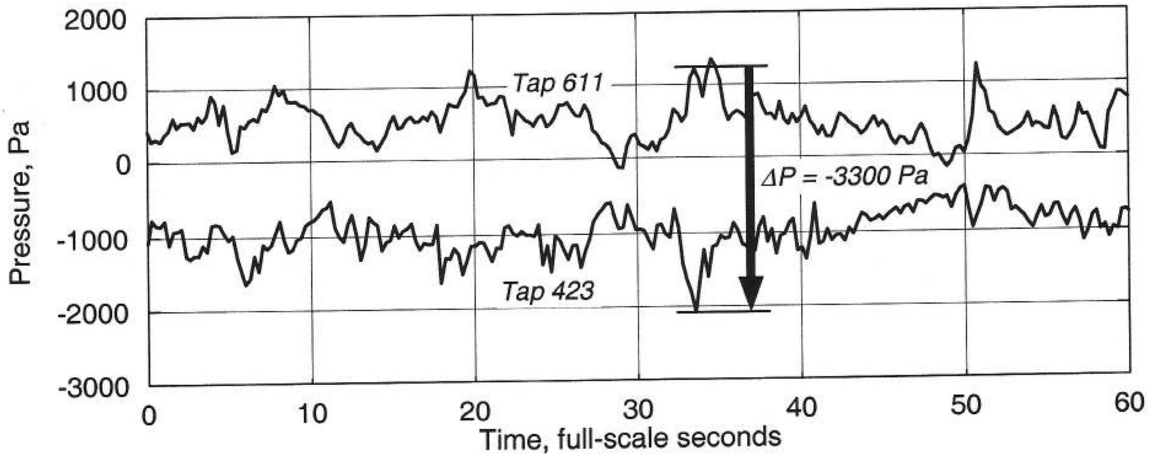

Figure 14: A typical example of simultaneous time-series pressure differences that were searched for maxima by wind direction and position on the curtainwall.

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). 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.

References:

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.

Bendat, J.S. and Piersol, A.G., "Random Data Analysis and Measurement Procedures", John Wiley & Sons, Third Edition, 2000.

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 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.

Irwin, H.P.A.H., "A Simple Omnidirectional Sensor for Wind Tunnel Studies of Pedestrian Level Winds", Laboratory Technical Report #LTR-LA-L42, National Aeronautical Establishment, National Research Council of Canada, 1980.

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.