# Architectural Aerodynamics:

# Wind Engineering and Tapering, Tilting, Twisting Towers

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The methodology of using small-scale models in a wind tunnel to produce structural loads and cladding pressures will be briefly discussed and then used to introduce the audience to the two recent trends in tall-building design and some consequences of those trends that impact the structural engineer. In recent times the field of super-tall buildings is being populated with residential buildings, whereas in the past they were nearly all commercial or office buildings. This impacts building design and performance expectations. How do residents respond to the upper-floor building accelerations that occur when living at 500 to 800 m? How does the engineer deal with the internal pressures generated at these elevations when operable windows are opened? Internal partition walls may commonly experience differential pressures in the range 2000 Pa to 3000 Pa, but the true value may be quite geometry dependent.

The second recent development is the explosion in architectural freedom created by drafting and analysis software that allows the architect to create spectacular shapes and the structural engineer to analyse them. Architects like Rem Koolhaas, Frank Gehry, Daniel Libeskind, Santiago Calatrava, Zara Hadid, Renzo Piano and Norman Foster may lead the field in spectacular designs, but they are not alone. Complexity in architectural shape abounds and it has some positive and negative impacts on how the wind creates the static and dynamic loads that the structural engineer needs to accommodate. The issue of wind-driven dynamic response of prismatic and complex shapes is becoming increasingly important. Does a tapered shape have dynamic as well as static load advantages? What about a twisting tower? Is the added complexity compensated for by the reduced dynamic loads?

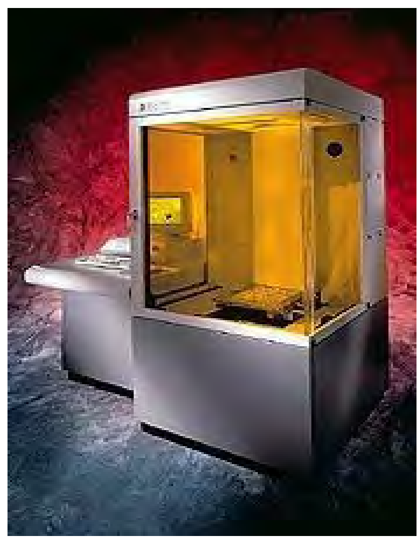

*Figure 1: The laser booth and operational console of a stereolithography machine used to make complex wind-tunnel models with pressure taps included.*

The physics of wind flow past various building shapes will be shown to illustrate the importance of wind-engineering input in the initial design of any building over 400 m – perhaps much shorter for very novel designs or in hurricane-wind environments. It is hoped that the variety of topics presented will generate some interesting discussions amongst attendees.

The use of the wind tunnel as a building design tool has become much more commonplace in recent years. Its effective use requires close coordination between the architect, the structural engineer and the wind engineer, with the architect traditionally serving as project leader. Many structural engineers find that the assessment of frame loads and local cladding pressures via physical modeling in the wind tunnel

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generates a better design with both improved confidence and economy in the final product. It is common to see cost savings in the structural and cladding design when compared to the code-based design – in effect the "money" is placed where it is needed when a site-specific, building-specific wind-tunnel study aids in the design process. Recent developments in wind-tunnel technology have expanded the usefulness of data generated for the architect and structural engineer and so allow the team, which includes the wind engineer, to explore unique geometries, unusual load combinations and dynamically sensitive structures, or portions of structures. In addition, the wind engineer is being consulted more frequently at the conceptual design stage when the building shape and orientation are being defined.

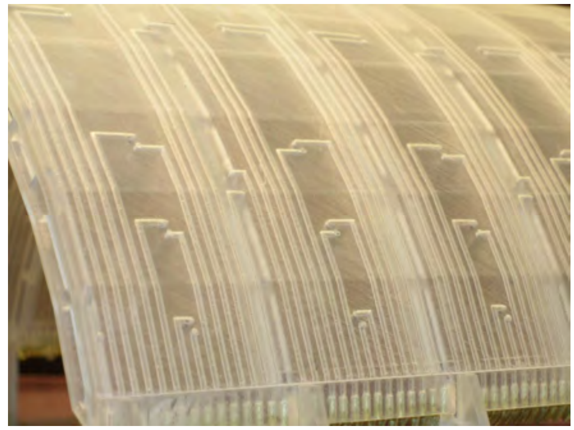

*Figure 2: Using the SLA process pressure paths may be "grown" into a curved surface for better pressure-data collection of this barrel-arched roof.*

## 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, with dual-curvature shapes, the ability to generate these elaborate shapes using software programs like AutoCAD, SolidEdge and SolidWorks allows the pressure tap paths to be incorporated into the design before the laser-induced creation of the physical model commences in the stereolithography vat (Figure 1). There is some skill on the part of the wind engineer in knowing the best way to design the pressure model components for useable pressure path lengths, appropriate strength in construction and optimal material volume, but the competitive cost of SLA models relative to the traditional Plexiglas models means that the vast majority of pressure models are now built using this method at most leading wind-engineering consultancies. Figure 2 show a portion of an open, barrel-arched roof with wind action on the top and soffit surfaces. Multiple tap pairs (one on each surface) may be used to estimate the net wind loads on this open glazed structure.

*Figure 3: Various types of tensile fabric structures lend themselves to physical modeling using the SLA process.*

## Force Measurements

Even with the popularity of simpler and cheaper aerodynamic models (both the high-frequency force balance technique and the simultaneous pressure approach – both discussed later) to assess dynamic structural loads there is still the occasional unconventional project that requires a fuller exploration of the complex nonlinear relationship between the structural response and the impinging wind via an aeroelastic study. Two interesting examples of this

"Rolls Royce" analogue solution to the governing differential equations of motion are the Atlas V Launch Vehicle (Figure 4) prior to lift-off and the architecturally decorative Houston Galleria Arches (Figure 5). 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 on board – thus, severely reducing the mass of the vehicle to be modeled. The mass scaling parameters in this condition dictated that a very light, thin, stiff, cylindrical 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. The technically related issues of circular-cylinder surface roughness (tripping separation of the flow around the launch vehicle) and Reynolds Number (ratio of inertia forces to viscous forces of concern to engineers when modelling flow over streamlined surfaces – unlike most bluff, sharp-edged building shapes which are far more forgiving) for this project came into play as well. A roughened, black surface in the payload area can be seen in Figure 4.

*Figure 4: Aeroelastic model of the Atlas V Launch Vehicle with the Mobile Service Tower backed away to the rear.*

A more Earth-bound, but equally interesting aeroelastic study was that of the Houston Galleria Arches in Figure 5. 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 to the turbulence flowing off the upwind arch. The seven most significant modes of vibration 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.

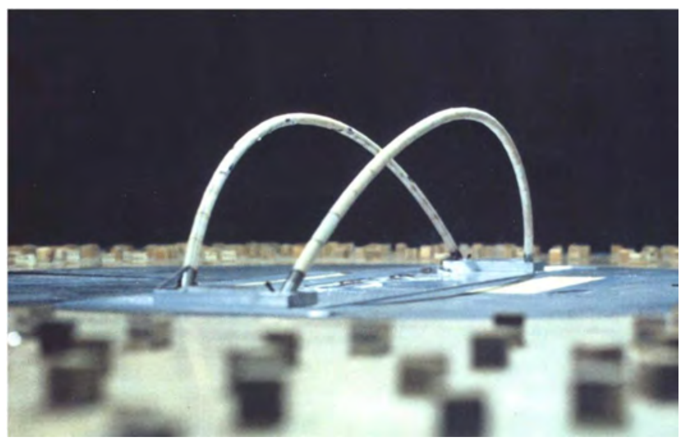

*Figure 5: Aeroelastic model of the Galleria Arches in Houston, Texas, were studied for wind-induced dynamic structural loads due to vortex shedding and aerodynamic interference with one another.*

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. This is usually referred to as the High Frequency Force Balance (HFFB) or the High Frequency Base Balance (HFBB) approach. 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 (Figure 6), 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*. Some readers will be fully familiar with this approach, but those who wish to read more are directed to work by Boggs [1] and many others in the wind-engineering literature.

*Figure 6: The lightweight, balsawood, HFFB model of the Repsol Tower in Puerto Madero is next to the cladding pressure model of Torre Manzana.*

However, what is relatively new in wind-tunnel studies is the availability of cheap pressure transducers (Irwin and Kochanski [2]), which convert the pressures caused by the wind at a point on the model into an electrical signal that may be stored in a data-collection computer for subsequent analysis. 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 façade areas, and moment arms to the global 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 that 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 would be approximately linear with height in the full scale but is constant with height on the force balance. Correction factors for these two shortcomings of the high-frequency force balance are available in the literature, but the

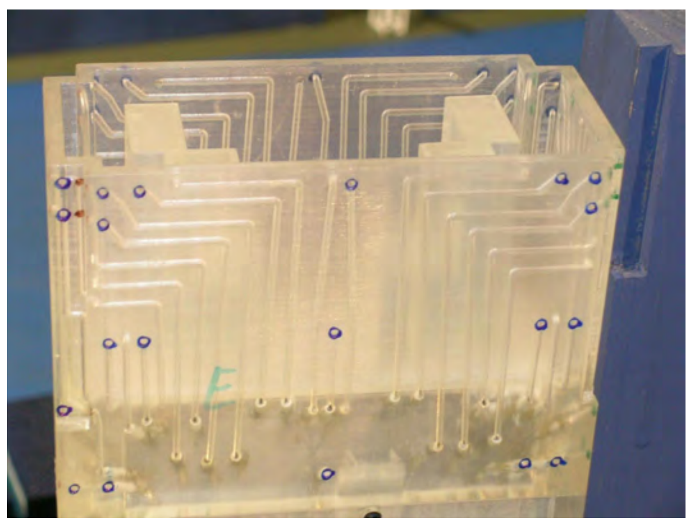

*Figure 7: The high screen or parapet walls on Torre Manzana were easily investigated using the SLA model and many simultaneous pressure measurments over 36 wind azimutths.*

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 the high-frequency force balance will generate base moments contaminated by roof uplift pressures at the model building extremities, well removed from the centrally located x and y axes. 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 (Torre Manzana in Figure 6 is an example), with a relatively small plan area, this effect is imperceptible. The simultaneous pressure technique removes the roof influence for long buildings 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, squat buildings do not lend themselves to the force balance and have plenty of internal volume for tubing.

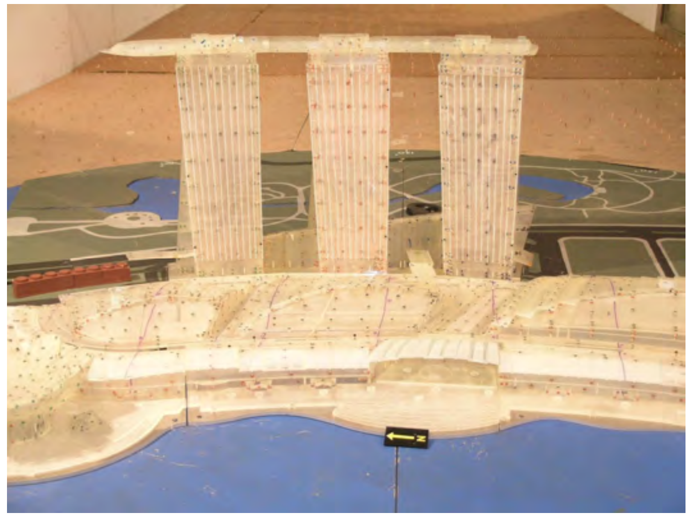

*Figure 8: Over 3000 pressure taps were used to assess wind loads on key portions of the Marina Bay Sands development in Singapore - including the rooftop "bridge" garden on the three towers and some large lowrise canopies.*

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 Inc., we have compared data collected using both the high-frequency force balance and simultaneous pressures for a variety of building shapes and surroundings. Those studies have suggested a relative insensitivity, beyond a threshold, 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 [3] also has some guidance of the number of taps needed.

*Figure 9: Thirty-storey Florida condominium, with tall proximate neighbours, used to compare balsawood force balance (shown here on the left as the twin building) data with the simultaneous pressure technique. The subject building is the middle one. Note that north is at the top of the photograph.*

Many comparisons have been made between the force balance and simultaneous pressure method approaches in more complex urban environments. Figure 9 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 10 and the spectral responses are in Figure 11 for the 200 degree wind azimuth. In this case only 290 taps on the pressure model of the tower were used. The comparison is fair, but the southerly flow (i.e. near 200 degrees) impacting the $M_y$ base moment indicates an underestimation on the mean (solid and dashed lines) and peak (open and solid symbols) base moments, probably due to the low number of taps used. For each wind azimuth there are two peak values (maximum and minimum extreme base moments) as well as a mean value between those extremes. Data like these have been used to suggest a lower bound to the number of taps needed. The sample spectra taken from the 200 degree load case in Figure 11 is in fair agreement between the two techniques, but again the $M_y$ data are somewhat larger for the mid-frequency range ($fD/U \approx 0.2$) for the HFFB results. These data, and other in-house studies, have led CPP Inc. to use between 400 and 700 taps in the typical simultaneous pressures study of a new midrise building in a complex cityscape. When this number of taps are used the data agreement is excellent.

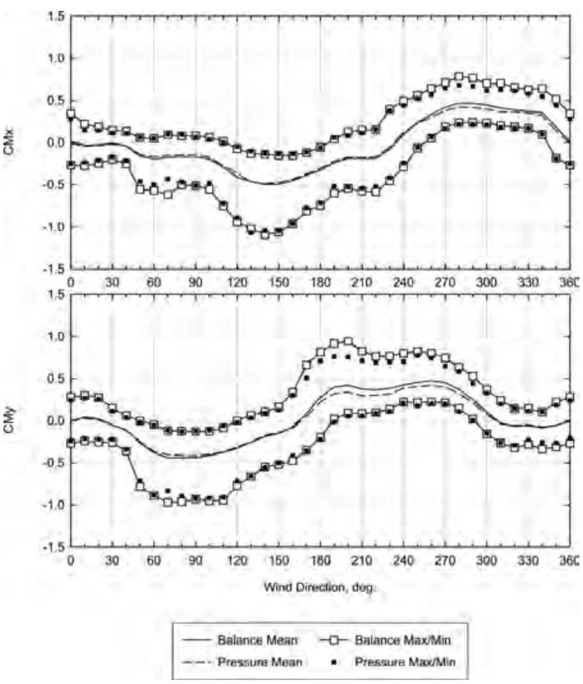


*Figure 10: Mean and peak base moment coefficients about the x and y axes using both techniques for the centre building in Figure 9. The mean and peak base moments are in generally good agreement except, perhaps, for southerly winds. More pressure taps will improve this agreement with the HFFB data.*

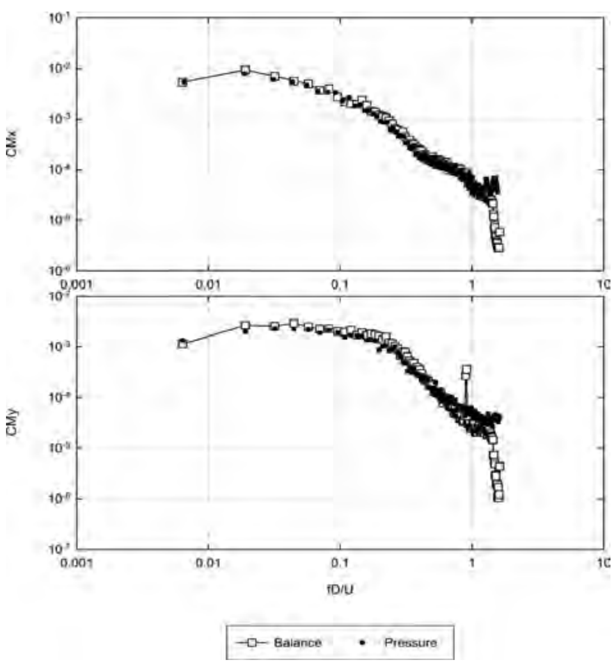


*Figure 11: Mx and My spectra from the HFFB and 290-tap simultaneous pressures at 200 degrees are slightly larger for the HFFB data in the mid-frequency range. This is consistent with the larger peak data in Figure 10.*

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 eight to twelve-storey range to be put in the wind tunnel. The unique home design in Figure 12 is an example of a lowrise building that does not lend itself to a code wind analysis, due entirely to the complexity of the architecture. This exotic, expensive, single-storey home has been tested in the wind tunnel. Although this is not a common client type, it does occur occasionally.

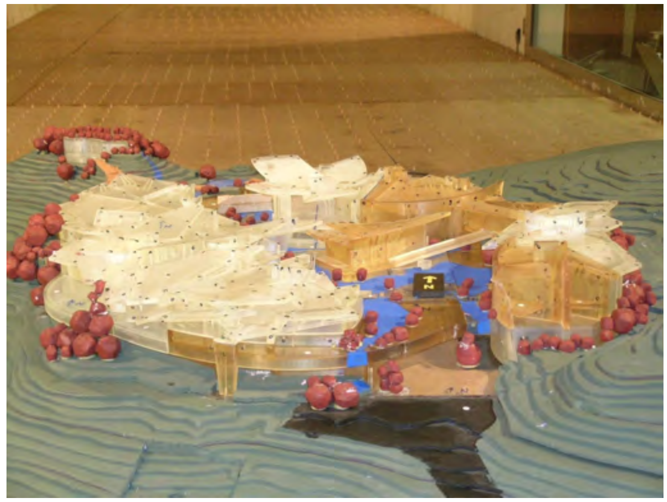

*Figure 12: A complex 1:100 pressure model of an expansive 4500 $m^2$ home in Palm Desert, California was built using the stereolithography process (Habitat Guy Dreier Designs).*

## Highrise Building Needs

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 buildings are likely to yield data in the near future. For example, there is a full-scale, GPS-aided, Chicago study of tall buildings being performed by researchers at Notre Dame University and the University of Western Ontario. Other full-scale, tall-building observations coming from researchers at the Hong Kong University of Science and Technology will help us understand building response more fully. This is particularly important as several current and future super-tall buildings exceed half a kilometer in height. Figure 13 shows Burj Dubai nearing its full height, and it is likely to be instrumented so that designers will have a better understanding of the response of the new generation of supertall buildings that are under construction and on the drawing boards.

*Figure 13: The huge Burj Dubai residential tower in UAE is likely to be instrumented for windspeed and building motion when completed.*

## Operable Facades and Green Buildings

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 [4]). 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 statistically lesser peak pressure difference serves better for a risk-consistent design. The building in Figure 14 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 15. Here a portion of a pair of simultaneous, time-series data that resulted in the largest pressure difference on one penthouse floor is shown and the largest difference was about 3.3 kPa for the 100-year design pressure. 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, and then these data are used in the façade design at the appropriate location on the glazed portion of the building.

*Figure 14: The Genzyme Headquarters in Boston, Massachusetts, was analyzed for cladding pressures when selected critical windows were assumed open during a design storm.*

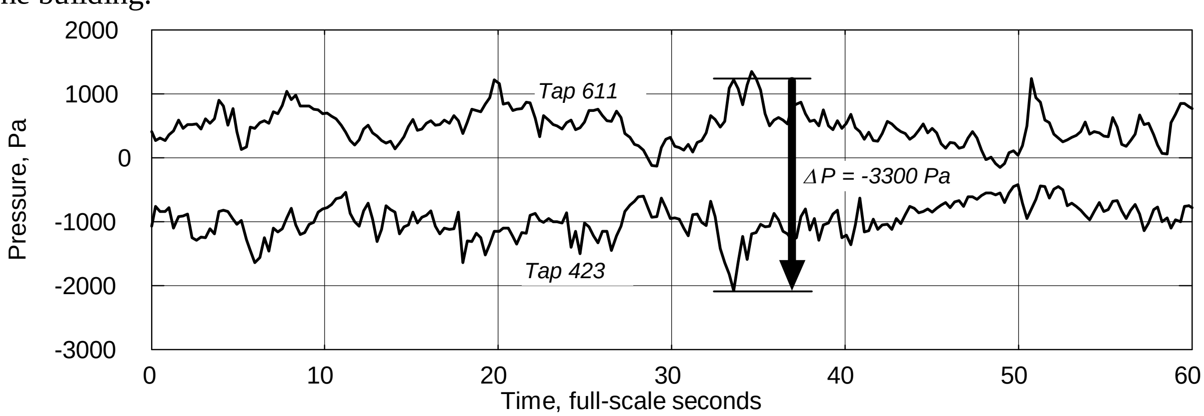


*Figure 15: A typical example of simultaneous time-series pressures that were searched for the maximum difference by wind direction and position on the curtainwall (after Cochran and Peterka [4]).*

Another internal pressure question has arisen in recent times with the advent of 300+ metre residential buildings (Figure 16). 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 and protected 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. Another residential tall-building issue is the perception of motion at the top of these tall apartment buildings. Some current work being performed in a motion simulator at the Hong Kong University of Science and Technology is likely to yield further insight into motion susceptibility of residents in these very tall apartment buildings.

*Figure 16: Residential buildings in the 300-m range generate new serviceability and partition design issues. Sunland Designs' Q1 in Surfers Paradise, Australia, is shown here.*

## Supertall Buildings

The increasing complexity of tall-building design is resulting shapes that break up the vortex shedding that often occurs with tall, exposed, prismatic designs. If the vortices shown in Figure 17 are not coherent up the height of the building then the crosswind response will be minimized. Such a decorrelation also avoids the increased dynamic loads created by synchronization of the shedding frequency ($f_s$) and the building's natural frequency ($f_o$). The Strouhal Number, defined in Figure 17, is made up of a typical crosswind dimension (D), local mean wind velocity (U) and the shedding frequency ($f_s$). The values of D and $f_s$ are, to some extent, functions of the design and so may be controlled by the design team. The value of U is a function of the local climatology and so is not typically a design parameter. Thus,

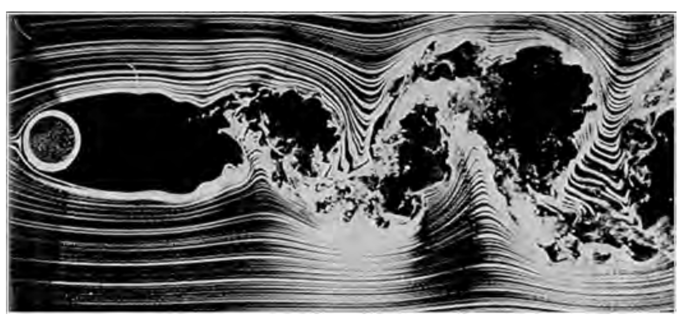

*Figure 17: Shapes other than the circular cylinder (shown here) also shed vortices to produce a crosswind response. The shedding frequency is a function of windspeed and building shape. This is defined by the Strouhal Number ($S_t = f_sD/U$).*

altering the building shape (in general or progressively up the height of the building) will impact the crosswind response. Different shapes (square, square with curved corners, circular, octagonal, triangular and rectangular) all have different Strouhal Numbers and differing spectra of crosswind response. The indicative values in Figure 18 show the substantial variation in crosswind response for some simple building prismatic shapes. For example, with a uniform, square section over the full building height we can see that for most reduced velocities it is structurally advantageous to stiffen the building (increasing $f_o$ and moving to the left down the spectra) to reduce the crosswind loads. If one changes shape over the building height the vortices are shed at different times and this decorrelation usually serves to diminish the crosswind response. Thus, on most super-tall buildings (Sears Tower, Petronas Towers, Burj Dubai, etc) we see an aerodynamically driven variation in building floor plate as a function of height.

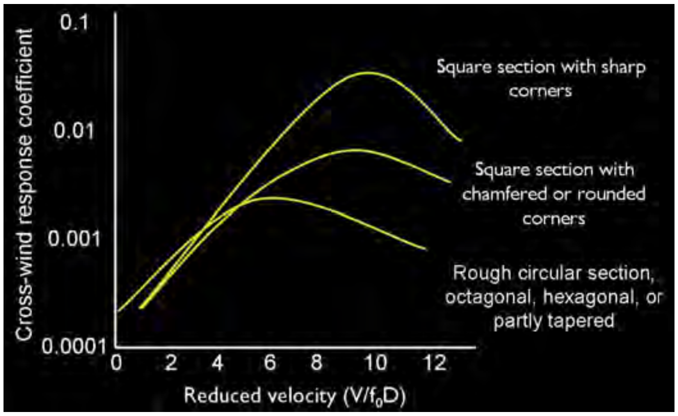


*Figure 18: Typical crosswind response for some simple prismatic building shapes as a function of reduced velocity.*

As with many aspects of engineering design there are competing “masters” in tall building design as well. Whilst, in general it may be advantageous to make the very tall building vary in shape over the height and to stiffen the structural system to reduce the correlation and impact of vortex shedding, respectively, a stiffer building will tend to place the upper-floor accelerations at frequencies that humans respond to more easily. Videos from the Hong Kong University of Science and Technology will be shown to illustrate this point. Thus, the designer has competing needs to balance. An increasing stiffness (larger $f_o$) will reduce the dynamic component of the load for the structural system, but a lower stiffness (smaller $f_o$) may make upper-floor acceleration perceptions better.

*Figure 19: Al Raha Beach Tower, Abu Dhabi, makes good use of varying the building section over the height to decorrelate, or "confuse" the wind.*

## Architectural Complexity

Architects are more able to conceptualize unique building shapes, and the structural engineer is more able to analyze these designs - both using sophisticated software. The result is often a tall building that is better able to resist the wind loads by diminishing the correlation of vortex shedding over the building height. Additionally, these twisted designs often lend themselves to better cross bracing over the building height – resulting in a more efficient design. As structural engineers and wind engineers are more exposed to tilting, twisting, dancing, tapered and “organic” designs we will learn a lot more about wind/structure interaction. Some ideas that are on the architectural horizon are in the following images.

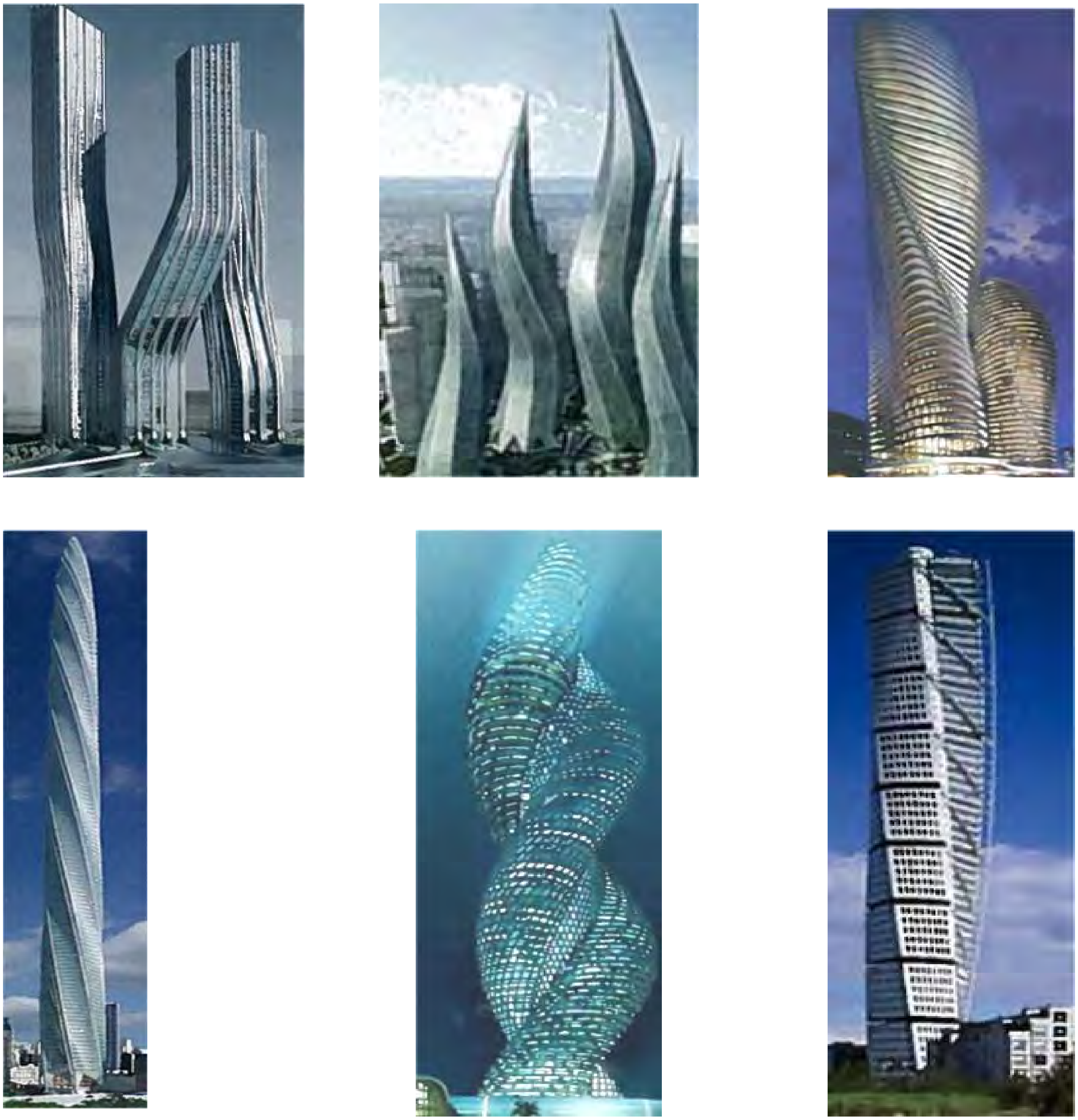

*Figure 20: Various proposed designs that push the bounds of wind and structural engineering from studios like Zara Hadid, TVS, PCA, Cobra and Calatrava (2).*

## Computational Wind Engineering

Lastly, the most obvious future development in commercial wind engineering will be the maturation of Computational Wind Engineering (CWE) – application of Computational Fluid Dynamics (CFD) to atmospheric flows. There is still much research to be done on turbulence models, solution algorithms, domain generation and gross computing power before structural loads and cladding pressures 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 some consultants, without much understanding of the wind or flow physics, are taking commercial programs, designed for low-turbulence internal flows, and are applying them to external, highly-turbulent, atmospheric winds around buildings (Cochran [5]). 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 has led some researchers to sarcastically refer to CFD as “Colourful Flow Drawings”.

The lack of validation with the full scale (as was done in the early years of wind-tunnel modeling) could easily mislead a well intentioned architect or 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, since they have a far better understanding of the turbulent, atmospheric flow physics. Even at this early stage there may be realms where CWE can positively contribute. For example, large-area meteorological flows over complex terrain (the use of nested grids used in codes developed by atmospheric scientists, such as Advanced Regional Predictive System (ARPS) from the University of Oklahoma or the Regional Advanced Modelling System (RAMS) from Colorado State University, as discussed by Derickson and Peterka [6]), thermally driven flows associated with internal atrium fires and certain smaller-scale dispersion studies seem to be the most likely first steps. *Thus, CWE is the way of the future, but wind engineers need to take the lead amongst 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*.

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