WIND EFFECTS ON LOWRISE BUILDINGS

Leighton Cochran, PhD CPEng[1]

Introduction

In the opening decades of wind engineering research and application the typical focus was on the glamorous, highrise structure. These expensive projects could typically afford the high cost of a wind-tunnel study. As the relative cost of these studies has decreased over the last forty years, more conventional architecture has found its way into the wind tunnel. However, it is still quite rare for a single-family dwelling to be studied, and when it does happen it is usually not just a typical home – rather it is an expensive architectural edifice. Sadly, the arrival of a major wind event, such as a cyclone or hurricane, inevitably results in far more wind damage and consequent financial loss to non-engineered lowrise homes and industrial buildings [FEMA, 1986 and 1992; Fujita, 1993]. In many countries these dwelling losses are not insured and so the social trauma is compounded even further. However, the *insured* losses from a variety of disaster mechanisms can be indicative of the importance of wind to the built environment. Figure 1 comes from Dr. George Walker, of AON Insurance, and it shows that well over half of all insured losses are wind related. This illustrates a worldwide need for better design for the natural wind.

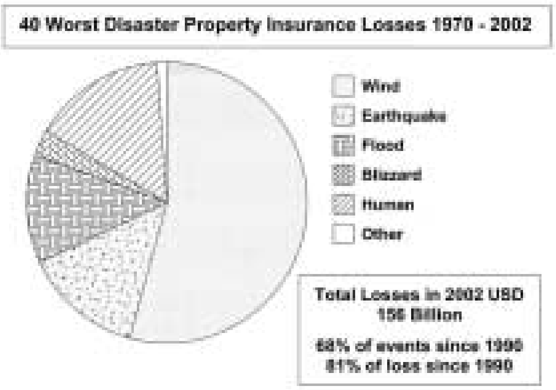

Figure 1: Worldwide insured wind losses [after Walker, 2003a and 2003b]

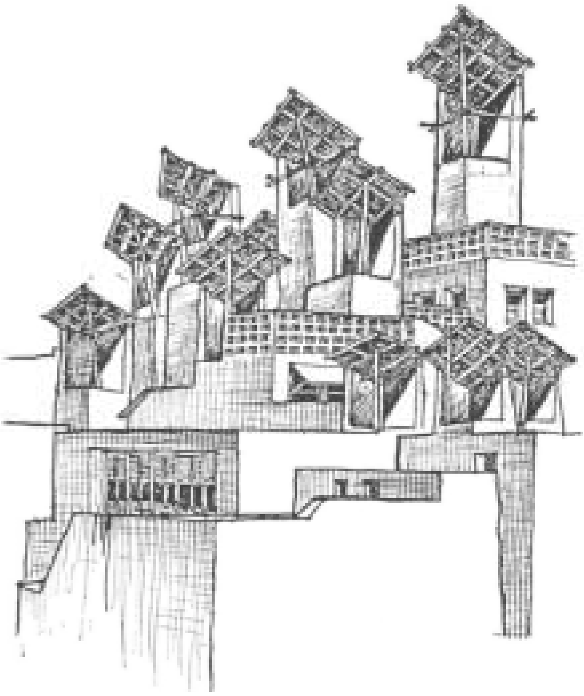

Figure 2: Air scoops in Hyderabad [after Aynsley Melbourne and Vickery, 1977].

The Past

The early grasp of wind motion and its consequences was steeped in mythology, which contained very little accurate observation. One of the earliest gods of wind dates back five thousand years to the Assyro-Babylonian culture and was referred to as

---

[1] Cermak Peterka Petersen Inc., 1415 Blue Spruce Drive, Fort Collins, Colorado 80524 USA.
Phone: [970] 221 3371, Fax: [970] 221 3124, Email: lcochran@cppwind.com

Enlil [Melaragno, 1982]. Since winds were often associated with the souls of the dead, human sacrifices were occasionally offered to calm the violent storm winds.

A practical use of the wind was achieved in some of the early Egyptian cities. The prevailing winds influenced the layout of the city of Kahun (circa 2000 BC). The orientation of dwellings to the cooler north winds favoured those with power and wealth in that society [Aynsley Vickery and Melbourne, 1977]. More recently in Hyderabad, India, the houses are designed with tall airshafts and modified air scoops on the roof that draw the breeze from above the city down into the homes (Figure 2).

The Greek philosophers, Aristotle and Theophrastus [Cermak, 1975] in the third century B.C., contributed their ideas to the cause of weather and its prediction. Aristotle's treatise, "Meteorologica", had little basis in physics but was very imaginative and, as Melaragno [1982] notes, "it lasted undisputed through to the sixteenth century". However, it was not until Leonardo da Vinci (1425-1519) produced, by quantitative observation and deduction, a genuine appreciation of the phenomena that any real progress was made. He grasped the concept of conservation of mass for an incompressible fluid and developed some early sketches of a variety of flying/gliding machines.

Further developments in the physics behind atmospheric motion became possible, as the instrumentation was invented to record the atmosphere's properties and characteristics. By the 1640s Galileo had invented the thermometer and Torricelli the barometer. These apparatus allowed works, such as Sir Francis Bacon's "Historia Ventorum", to challenge Aristotle's writings.

No real attempt to quantify the motion and properties of fluids was possible until Sir Isaac Newton had developed the concepts of mechanics. For example, he correctly observed that the resistive force on an object in a fluid is proportional to the square of the velocity of the fluid passing it. This result is of particular use for bluff bodies at modest to high Reynolds number. The analysis of continuum mechanics was developed by a mixture of mathematicians and hydraulicians such as Bernoulli, Euler, d'Alembert, Navier, Stokes, Cauchy, Poisson, Reynolds and Joukowski to mention a few (see Table 1). The most general formulation of the equations of motion is attributed to the French mathematician, Claude Louis Marie Henri Navier, and the British physicist, Sir George Gabriel Stokes. Analytical solutions to these equations are limited to simple geometries and well-defined fluid properties. Examples of these flows may be found in many fluid dynamics texts [Yih, 1988; Karamcheti, 1980]. Since, for most engineering applications, the ideal fluid solution was analytically unobtainable or apparently in conflict with common sense (d’Alembert’s paradox below) many designers had to resort to physical testing. One case in point is the design and construction of the Parisian Eiffel Tower, which subsequently resulted in considerable atmospheric science and aeronautical research. Eiffel's experiments in bluff body aerodynamics and his wind load design assumptions for the Paris Exposition Tower were amongst the earliest attempts to understand static wind loading.

At about the same, time Ludwig Prandtl presented his famous paper, "Uber Flussigkeitsbewegung bei sehr kleiner Reibung", at the 1904 meeting of the International Mathematical Congress in Heidelberg. An apparent impasse existed between the theoretical, newly termed field of "fluid mechanics" and the empirical results of hydraulics. The most dramatic example of the inconsistency between theory and practice is referred to as d'Alembert's paradox. The apparent lack of drag predicted by the mathematical analysis of irrotational flow around a body was at odds with practical experience. Prandtl's proposal to consider two adjacent, asymptotic regions of a fluid acting around a body resulted in reconciliation between observation and the equations of motion. One of his most famous students was Theodore von Kármán, who initially studied solid mechanics, before moving on to make great contributions to the field of aerodynamics [von Kármán, 1967]. Prandtl constructed a small wind tunnel in 1908 at Gottingen, and so the concept of aerodynamic model testing was put on a more scientific footing. Prior to this some bluff body building studies had been attempted in primitive wind tunnels by Kernot [1893], Irminger [1894] and Eiffel, as noted above.

The viscous components in the equations of motion were assumed to be significant in a thin region of flow at a close proximity to the surface over which the fluid moved. This allowed for a non-slip condition at the surface with progressively increasing velocities as one moves from the surface into the free stream flow. The region was described by the term, "boundary layer", and its asymptotic nature required some definition of extent. One that is commonly in use is the distance from the surface at which the velocity assumes ninety-nine percent of the free stream flow [Schlichting, 1978]. Outside this boundary layer it was proposed that the classical inviscid solutions could be applied.

However, the application of wind-tunnel testing to ground based structures took five more decades to become a useful engineering tool. In fact, the term "Wind Engineering" was not coined until the early 1970s at the first United States National Conference on Wind Engineering Research. Prior to this development the field was a subset of the larger topic of "Industrial Aerodynamics" [Scruton, 1960; Cermak and Peterka, 1978]. Initially studies were performed in a uniform flow, which produced spurious results. Probably the most quoted example is a paper by Bailey [1935]. By the 1950s atmospheric studies of the Earth's turbulent boundary layer had led to a greater understanding of its complexity and the establishment of a better set of modeling criteria. Cermak [1958] demonstrated the criteria for Reynolds number independence when modeling an atmospheric boundary layer flow at a reduced scale. The application of statistical concepts, developed by Davenport [1961], was an essential contribution to physical modeling in wind engineering. Building studies were performed frequently by the late 1960s, and the theoretical justification for such work is contained in papers by Cermak [1971 and 1981]. In brief, it had been observed that the Reynolds number drag dependence for bluff, sharp edged bodies (and the boundary layer itself) was small when performed above a critical Reynolds number. Thus, a major similarity requirement could be waived and the test results would still be of value. The insensitive nature of load coefficients to Reynolds number meant that boundary-layer, wind-tunnel modeling was viable at moderate wind speeds.

Figure 3: Testing the World Trade Center Towers in 1964 in a boundary-layer wind tunnel at CSU. The people are (left to right): A.G. Davenport, M. Yamasaki, M. Levy, J. Skilling, J.E. Cermak and L.E. Robertson (Colorado State University archives).

Concurrent studies into the effects of turbulence and how to measure it had been progressing from as early as Schubauer and Dryden [1935] to more recent work by Van der Hoven [1957] and Monin and Obukhov [1954]. The turbulent spectrum of the natural wind led to a growth of modeling from static building studies to dynamic investigations. The description of the energy content of the wind via the turbulence spectrum by Davenport [1965] was an essential concept that pushed Wind Engineering from static to dynamic studies. During the 1940s and 1950s dynamic wind-tunnel studies were generally limited to flexible, long-span bridge structures.

Table 1: Some Key Events in Wind Engineering

Year	**Researcher**	**Event**
1643	Torricelli	Invents barometer
1687	Newton	Defines viscosity, laws of motion, calculus, Principia
1738	Bernoulli	Defines conservation of energy in fluids, Hydrodynamica
1755	Euler	Form inviscid equations of fluid motion
1806	Beaufort	Defines wind-speed in term of visible effects
1836		**Collapse of Brighton Chain Pier by oscillatory motion**
1845	Stokes	Formulates Navier-Stokes equations of fluid motion
1846	Robinson	Invents cup anemometer
1879		**Collapse of the Tay Bridge in Scotland**
1883	Reynolds	Dimensionless parameter that indicates onset of turbulence
1888	Dines	Invents pressure tube anemometer
1904	Prandtl	Develops the boundary-layer concept
1912	von Kármán	Identifies vortex shedding in wakes
1914	King	Defines equation for cooling of hot cylinders
1928	Fisher & Tippet	Develop theory of extreme values
1934		**Highest measured gust at Mt. Washington (370 km/h)**
1935	Taylor	Develops statistical theory of turbulence
1940	Rathbun	Collected full-scale deflections on the Empire State Building
1940		**Collapse of Tacoma Narrows Bridge by oscillatory motion**
1954	Cermak	Builds first large boundary-layer wind tunnel
1954	Jensen	Formulates model scaling laws
1957	Van der Hoven	Compiles wide frequency range spectrum of the wind
1958	Cermak	Reynolds number independence in modeling boundary layer
1961	Davenport	Develops statistical concepts to wind loadings
1963		**1st International Conference on Wind Effects on Buildings**
1964	Cermak & Davenport	First major building study in a boundary-layer wind tunnel – The World Trade Center Twin Towers in New York City
1965		**Collapse of three cooling towers at Ferrybridge**
1970		**Term “Wind Engineering” coined**
1974	Eaton & Mayne	Aylesbury House study in Britain
1976	Deaves & Harris	Develop mathematical model for strong winds
1979	Melbourne	Shows importance of turbulence in bluff-body aerodynamics
1986		**Amarube Tekkyo rail bridge disaster in Japan**
1984	Holmes	Defines wind-tunnel pressure tubing response characteristics
1987	Mehta	Texas Tech University Experimental Building is built
1988	Robertson & Glass	Silsoe Structures Building is built
1992	Murakami	1st Computational Wind Engineering Symposium, Tokyo

Sources: Aynsley Vickery and Melbourne [1977], Britannica [1968], Cermak [1975], Melbourne [1979], Cochran [1992], Cook [1985], Holmes [1984], McWhirter [1986], Takagi [1992] and Timoshenko [1953]

This was particularly true after the dramatic failure of the Tacoma Narrows Bridge. It is worth noting that this mechanism of torsional failure was not a new phenomenon (see Table 1). The transition from dynamic bridge to dynamic building studies was principally motivated by the decision to build the twin towers of the World Trade Center (Figure 3) in New York [Davenport, 1988; Cochran, 2002].

Instrumental in the development of dynamic studies was the ability to observe the passing turbulence structure using hot-wire anemometry. The initial heat transfer analysis was performed by King [1914], but the technique was seriously limited by practical electronic considerations for two more decades [Dryden and Kuethe, 1920]. The work of Schubauer and Klebanoff [1946] showed that the high frequency response possible with better electronics was of practical value. A brief discussion of this topic is given by Hinze [1975], Bradshaw [1971] and a far more detailed synopsis by Sandborn [1972 and 1981].

Wind Loads on Lowrise Buildings

Since lowrise structures frequently equate with being low-cost structures most designers simply accept the pressure coefficients presented in the relevant code of practice. However, the recent trend in the use of fabric structures or other unconventional lowrise design (Figure 4) has resulted in unusually shaped lowrise buildings, of modest or substantial value, being tested more commonly in boundary-layer wind tunnels. Thus, there is some additional motivation to be able to model the atmospheric, surface-layer flows beyond the simple improvement of the currently available code data for quasi-rectangular structures.

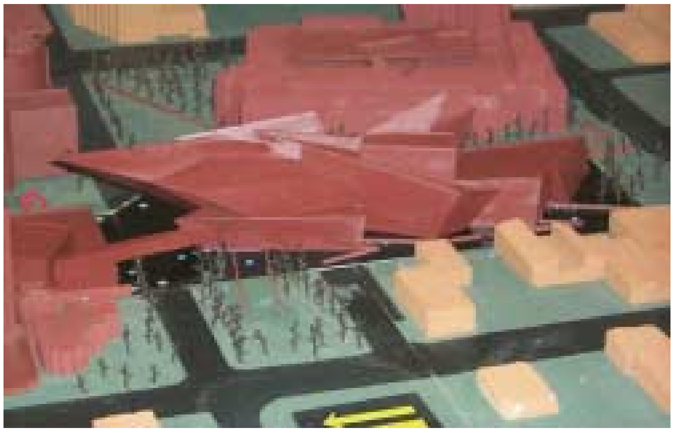

Figure 4: The Denver Art Museum is a non-typical shape, and applying a code procedure is inadvisable (after CPP Inc.).

In an effort to improve the codified pressure data for lowrise structures and, of course, to confirm the commonly used wind-tunnel procedure, the Aylesbury House Experiment was undertaken in Great Britain. Eaton and Mayne [1975] describe an extensive full-scale experiment on several two-storey homes in Aylesbury, 65 km northwest of London, England. The principal contribution to wind engineering that came from this project was an experimental building with a variable pitch roof. Most of the pressure data were collected on this building and some on three downwind dwellings. Subsequently many laboratories around the world have tested models of the Aylesbury House [Holmes, 1982b]. The Aylesbury experimental building was built upwind (relative to the prevailing winds) of a suburban area, and so had an open exposure for frequent, strong winds. The reported Aylesbury House range of z_o varied from 50 to 150 mm. In this way the data from the exposed experimental building could be compared with that collected in the complex environment of the downwind housing estate. The reference pressure was taken from a common in-ground pit located between the isolated house and the estate downwind. The site of a reference pit and its design are frequently problems associated with full-scale measurements [Levitan, 1992] and the Aylesbury house was no exception. Eaton and Mayne believe that there was a slight under-reading of the actual ambient pressure by the pit design that was used; about 8% of the 10 m stagnation pressure.

Holmes [1982b] discusses some of the full-scale results from the Aylesbury building and the subsequent international model study. The full-scale turbulence intensity at eaves height ranged between 22% and 27% for the southwest to south wind and he is of the view that turbulence intensity is an "important parameter to be scaled correctly in the wind tunnel test", while the longitudinal integral length scale similarity "does not seem to be a parameter of the greatest importance". A summary of the international comparative study of the 1:100 model of the Aylesbury House is given by Sill and Cook [1989].

A full-scale study performed on residential homes at the Malmstrom Air Force Base in Montana is reported by Marshall [1975], as well as a second study on full-scale mobile homes [Marshall, 1977]. In the former, the mean data were in reasonable agreement between the model and full scale, although some correction was required for the siting of the static pressure source. However, the serious mismatch of turbulence intensity resulted in peak pressure coefficients that were consistently deficient in the model studies. The full-scale turbulence intensities ranged from 27 to 38%, while the wind-tunnel flows varied from 6 to 31%. Marshall [1975] writes,

> "The consistently low fluctuating pressure coefficients obtained from the wind tunnel model are attributed to improper simulation of the lower portion of the atmospheric boundary layer"

Reardon and Holmes [1981] give a synopsis of their research on low-rise structures performed at James Cook University (JCU). The authors discuss trends noted in the JCU boundary-layer wind tunnel in a variety of flows and model geometries. Some of their pressure related conclusions include:

> (i) For flows perpendicular to a wall, a more turbulent environment resulted in closer reattachment, more free streamline curvature and lower pressure, and
>
> (ii) For quartering flows the action of the vortices was enhanced by roof overhangs.

At the same institution [Reardon, 1997] fatigue failure on industrial and residential lowrise buildings noted during the slow passage of Cyclone Tracy over Darwin in 1974 resulted in research in the area of metal cladding fastener failure with repeated, cyclic, gust loading [Mahendran, 1990]. Of particular relevance to the design of lowrise buildings in cyclone areas is the commentary by Reardon and Holmes [1981] on the siting of the extreme roof suctions.

> "The worst mean roof suctions, independent of direction, occur along the edges near the windward corner, but not at the corner itself"

This foreshadowed detailed research and observation on roof corner vortices at the Texas Tech University (TTU) Building in Lubbock during the early 1990s. However, before that project was built some key full-scale research was performed on the Silsoe Structure Building in England.

The Silsoe Structure Building is described by Robertson and Glass [1988] and Richardson Robertson Hoxey and Surry [1989]. It was a portal framed, low-rise structure that featured two types of eave cladding detail. The approaching wind has a clear open country fetch (except for some hedge windbreaks) from the southwest to the northeast in a clockwise arc. The Silsoe z_o varied from 10 mm to 43 mm over the duration of the project. The longitudinal turbulence intensity at 10 m elevation was in the range 20 to 23% and the transverse turbulence intensity ranged from 17 to 18%.

The wind-tunnel studies of the Silsoe Structure Building, performed by the Building Research Establishment (BRE), were taken with a sample rate of 200 Hz and the total number of samples taken per run was 16000. The models were then retested at the University of Western Ontario (UWO) at a higher sampling rate (500 Hz) and with more data points (30000). The mean data taken on the full-scale Silsoe Structure Building fell in between that measured at BRE (underestimated by 30%) and UWO (overestimated by as much as 50%) for some locations on the roof in the rougher approach flow. It should be noted that the shape of the pressure plots was all very similar; the data were simply displaced (Richardson Robertson Hoxey and Surry, 1989). The Silsoe positive pressure coefficients on the windward wall had generally good agreement between all investigators. The data published were only for a centreline row of taps across the building with the wind impinging on the long side. No azimuth dependencies were shown. More recently the two laboratories revisited the model and full-scale data, including directional dependency, in a paper by Richardson Hoxey Robertson and Short [1997] where they show better agreement between the three mean pressure coefficient data sources.

Surry [1989] reported on wind tunnel studies of the TTU Building performed at the University of Western Ontario prior to any full-scale data being available, and Okada and Ha [1991] presented data collected at the Building Research Institute in Japan.

The study by Okada gave good mean pressure coefficient agreement with the full scale, but the magnitudes of the peak and rms data were significantly less than were reported at TTU in Lubbock. The data were reported for normal flow orientations only. Okada attributes the mismatch in peak and rms data to a combination of two modeling limitations. His turbulence intensity was only 75% of that recorded in the field and, as noted above, this is an important parameter for peak pressure measurements in the wind tunnel. In addition, the long tubing system and Scanivalve used to collect the data required a low-pass filtering at 50 Hz. When combined with a modest sample rate of 100 Hz, the collection of reduced peak and standard deviation pressure coefficients would be expected [Rofail and Kwok, 1991].

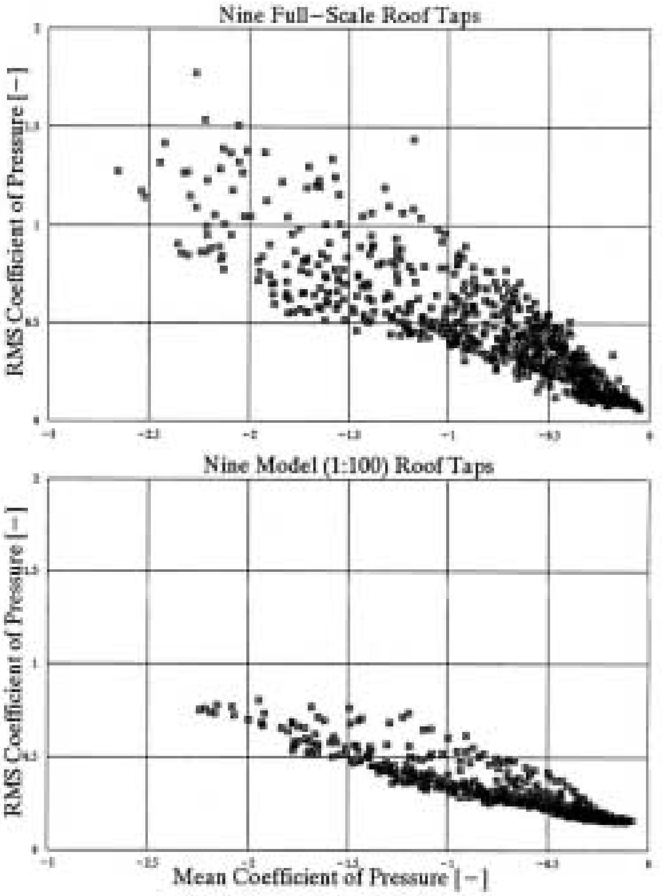

Figure 5: Pressure coefficient standard deviations, under the corner vortices, in the full-scale are substantially larger than in the wind tunnel. Reynolds Number influence is apparent with vortices in the wind tunnel [Cochran, 1992].

The data reported by Surry [1989] were collected "in advance of the full-scale data" so as to "partly provide an 'unbiased' set of pressures for comparison". Surry's motivation for this procedure was to avoid the subtle, but real, observation that "model experiments are often a matching process, where wind-tunnel simulations are varied until reasonable agreement is obtained, rather than being truly independent simulations". The 1:100 model tested at UWO was exposed to two flow regimes. The flow designated "exposure #2" most closely matched that seen at the TTU field site and the free-stream flow velocity used in the tunnel was 14 m/s. The tubing system was of modest length (610 mm) and included a Scanivalve. Consequently low-pass filtering at 100 Hz was employed. At a relatively high sample rate of 500 Hz this tubing system was adequate to capture all the peak pressure coefficient data available in the wind tunnel flow. In fact, a tubing system with an improved frequency response did not alter the peaks greatly [Surry, 1991]. All the pressure data (mean and peak) from the 90^{o} flow case of Surry's study are in good agreement with the TTU full-scale data. However, the data presented for the "near 60^{o}" flow direction show significant disagreement over the centreline taps. The peak suctions on the model were about 40% less than the values at full scale. This was an early indication of the mismatch of peak pressure coefficients that occurs when the dominant flow mechanism is the roof corner vortex.

Figure 6: Roof corner vortices produce large peak uplift pressures (after CPP Inc.)

Cochran [1992] and Cochran and Cermak [1992] showed the peak pressure coefficient mismatch, under the roof corner vortices, between the small-scale wind-tunnel study of the TTU Building and the prototype, and also explored a variety of possible explanations. Figure 5 shows the much larger variation in the standard deviation pressure coefficient (sometime erroneously called an rms pressure coefficient) under the full scale than on the wind-tunnel model. By using an area-averaging “super pressure tap” on the prototype building, Cochran Levitan Cermak and Yeatts [1993] demonstrated that the pressure coefficient recorded was influenced by the size of the tap on the model or full-scale building – particularly when the flow phenomenon is comparable in size to the pressure tap. It seemed most likely that the local Reynolds Number mismatch at the point of vortex origin results in relatively weaker vortices on the model than in the full scale. The impact of approach turbulence is also an important parameter and it was explored by Li and Melbourne [1996]. A better matching of peak negative pressure coefficients may also be achieved with larger model scales (e.g., 1:10 of the TTU building) in the wind tunnel, as demonstrated by Cheung Holmes Melbourne Lakshmanan and Bowditch [1997]. The corner vortex mismatch mechanism has had no real impact on the general wind-tunnel testing of buildings for cladding pressures, since the glass pane or piece of roof sheeting that is being designed near the building corner (wall or roof vortices) is much larger than the relative pressure tap size. Thus, as a result of full-scale area averaging the wind tunnel yields the right design pressures for the wrong reasons. This observation is supported by noting that the extreme event pressure failure, on buildings that have been wind-tunnel tested, is very rare.

Over the last decade, the extensive work done on the TTU Building in Lubbock has allowed a better understanding of the importance of internal pressures on the net pressure to be resisted by the cladding material. Investigators have experimented with internal pressures generated by façade leakage [Womble Cermak and Mehta, 1997] and by catastrophic glazing failure [Yeatts and Mehta, 1993]. Interest in the integrity of the building envelope has also resulted in a surge of practical research at Clemson University on a variety of hurricane related problems [Sutt Reinhold and Judge, 2000].

More detailed and varied reviews of lowrise wind-engineering research may be found Stathopoulos [1984], Holmes [1993 and 2001], Krishna [1995], Kasperski [1996], Stathopoulos Kumar and Mohammadiam [1996] and Uematsu and Isyumov [1999].

Wind Load Reduction Via Architectural Features

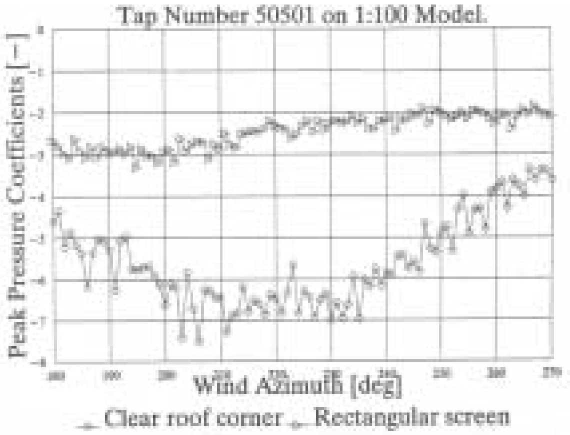

Figure 7: A porous screen at the roof corner of the TTU Building dramatically reduces the peak uplift pressure coefficients by destroying the vortices.

Research into wind loads and cladding pressures on lowrise buildings has spawned some novel geometries and protrusions to be designed and tested in order reduce the peak uplift pressures by altering the separated streamlines or destroying the roof corner vortices via porous fences and leading-edge spoilers. Work by Wu Sarkar and Mehta [2001] and Wu Sarkar Mehta and Zhao [2001] explored the corner vortex in the full scale, while Cochran Cermak and English [1995] (Figure 7) and Surry and Lin [1995] show methods for breaking up the roof vortices using various designs of porous screens, porous parapets and roof-edge circular cylinders. Banks Sarkar Wu and Meroney [2001] study the vortices in the wind tunnel in considerable detail and investigate some ingenious and visually subtle spoilers (US Patent 6,601,348) along the roof edge to achieve a reduction in peak negative pressures along the roof leading edge. A better understanding of the loading mechanism of the cladding components can lead to a better roof design. For example, a common roofing material in North America, the asphalt shingle with the overlapping tabs used to keep rain and snow out of the building, does not form a locally airtight membrane that must resist the entire peak pressure dictated by a wind code calculation. In fact, wind-tunnel and full-scale studies have shown that there is a high degree of peak pressure equilibration between the top and bottom surface of each shingle tab (Peterka Cermak Cochran Cochran Hosoya Derickson Harper Jones and Metz, 1997). Thus, shingle roof design has been improved with knowledge about the mechanism loading the roof elements themselves. The same is true of loosely placed concrete pavers on a horizontal roof (Bienkiewicz and Sun, 1992), and may be true of clay and terracotta tiles which, it is believed, have been studied in England.

Some researchers have suggested a holistic building shape approach to minimize wind loads on the whole building. Cook [1990] suggests a brick home with perimeter wall, roof and balcony alignments designed to provide the wind with a path of least resistance in order to minimize design loads. Leicester and Reardon [1976] show an experimental home designed with wind as the dominant consideration that failed during Cyclone Tracy in Darwin because of inadequate component fasteners. The shape *may* have been a good idea, but the lack of attention to detail failed the whole system – a powerful example of Davenport’s chain and link metaphor.

Knowledge Gaps and Special Cases in Design Wind Loads

Much of the full-scale, wind-loading data collected to date has been in an open-country environment. However, the vast majority of lowrise buildings are in amongst their peers, not isolated out in a field. Thus, the study of full-scale buildings within a suburban environment would be an obvious future direction. Some researchers have touched upon the topic of lowrise building shielding by similar sized neighbours, and the impact of being at the field edge compared to a surrounded location [Kasperski Niemann and Goliger, 1999]. The impact of a field of similar structures surrounding a subject structure was the topic of extensive studies in the 1980s for the fledgling solar power industry [Hosoya, 1983; Peterka and Derickson, 1992]. This resulted in a way of describing the design loads in terms of a Generalized Blockage Area (GBA) within the field of similar structures. Isolated, pole-mounted, tracking, concentrator, photovoltaic solar collectors were studied by Cochran [1986], and when they were mounted on a building the detailed pressure distributions and interactions were investigated by Kopp Surry and Chen [2002].

Letchford [2001] provides a useful discussion of wind loads on freestanding signs and hoardings, while Yaragal Ram and Murthy [1997] discuss the flow regime behind porous and solid fences. Full-scale, long-wall experiments are ongoing at the Silsoe facility in England [Robertson Hoxey Short Ferguson and Osmond, 1995].

Figure 8: North-facing Kauai valleys on the 1:6000 model yields topographically accelerated winds at the inland rim locations (after CPP Inc.).

Lowrise buildings are routinely adversely impacted by the speed-up effect caused by terrain, as noted by Davenport [1993]. Some codes contain a two-dimensional attempt to account for the increased velocity caused by hills and escarpments, but they typically fall short of reality. An extensive wind-tunnel terrain study of the Pacific Islands of Hawaii and Guam by Chock Peterka and Cochran [2002] for NASA showed that wind funneled up a diminishing valley (Figure 8) will eject surface peak velocities of about 250% of the mean gradient approach flow over the ocean [Chock and Cochran, 2004]. Accelerated winds over complex terrain in hurricane/cyclone areas needs to be better understood to aid in post-disaster response, and well as the obvious initial design of the lowrise buildings. Derickson and Peterka [2004] have shown that value of combining nested-grid, continental-spanning, atmospheric computational packages (such as ARPS) with physical modeling of local complex terrain in the wind tunnel to explore extreme wind event speed-up due to topography.

Conclusions

Over the last two decades Wind Engineering has increasingly focused on the modest lowrise structure, since much of the damage and financial loss associated with extreme wind events happens to these minimally engineered buildings. As some of these model- and full-scale wind engineering data filters into the design codes and standards, one may expect to see reduced hurricane/cyclone damage. However, when one combines the more rapid increase in population along the world's tropical coasts with a generally unacceptably low standard of new building construction inspection, it seems quite likely that loss of life, as well as insured and uninsured property losses will continue to be the norm in the foreseeable future. The wind-engineering community needs to be more responsible in forcefully transferring our technical knowledge to the designer and builder. A booklet with the aim of explaining, in simple terms, the wind effects on structures to the architect, builder and inspector, is going to be published by ASCE in 2005. This sort of direct information, along with passionate political lobbying, is needed to mitigate the unacceptable loss of life and financial loss (Figure 1) caused by the extreme wind event.

References

Aynsley, R.M., Melbourne, W. and Vickery, B.J., "Architectural Aerodynamics", Applied Sciences Publishers Ltd., London, 1977.

Bailey, A., "Wind Pressures on Buildings", Institution of Civil Engineers, selected engineering paper No. 189, 1935.

Banks, D. and Meroney, R.N, "A Model of Roof-Top Surface Pressures Produced by Conical Vortices: Evaluation and Implications", Wind and Structures, Volume 4, Number 4, pages 279-298, 2001.

Banks, D., Sarkar, 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, 2001.

Bienkiewicz, B. and Sun, Y., "Wind-Tunnel Study of Wind Loading on Loose Laid Roofing Systems, Journal of Wind Engineering and Industrial Aerodynamics, Volume 43, pages 1817-1828, 1992.

Bradshaw, P., "An Introduction to Turbulence and its Measurement", The Commonwealth Library of Science Technology Engineering and Liberal Studies, Pergamon Press, First Edition, 1971.

Britannica Encyclopedia, 1968.

Cermak, J.E., "Wind Tunnel Design for Physical Modeling of Atmospheric Boundary Layers", Journal of American Society of Civil Engineers, Volume 107, No. EM3, June 1981.

Cermak, J.E., "Application of Fluid Mechanics to Wind Engineering", A Freeman Scholar Lecture, Journal of Fluids Engineering, American Society of Mechanical Engineers, Volume 97, No. 1, March 1975.

Cermak, J.E., "Laboratory Simulation of the Atmospheric Boundary Layer", American Institute of Aeronautics and Astronautics Journal, Volume 9, pages 1746-1754, September 1971.

Cermak, J.E., "Wind Tunnel for the Study of Turbulence in the Atmospheric Surface Layer", Technical Report CER58-JEC42, Fluid Dynamics and Diffusion Laboratory, Colorado State University, 1958.

Cermak, J.E. and Peterka, J.A., "Wind Engineering; Applications to Civil Engineering", American Society of Civil Engineers Convention and Exposition, Preprint 3452, Chicago, October 1978.

Cheung, J.C.K., Holmes, J.D., Melbourne, W.H., Lakshmanan, N. and Bowditch, P., "Pressures on a 1/10 Scale Model of the Texas Tech Building", Journal of Wind Engineering and Industrial Aerodynamics, Volume 69-71, pages 529-538, 1997.

Chock, G.Y.K. and Cochran, L.S., "Modeling of Topographic Wind Speed Effects in Hawaii", Journal of Wind Engineering and Industrial Aerodynamics, 2004 (in press).

Chock, G.Y.K., Peterka, J.A. and Cochran, L.S., “Orographically Amplified Wind Loss Models for Hawaii and Pacific Insular States, NASA Contract NASW-99045, March 2002.

Cochran, L.S., “Early days of North American Wind Engineering: An Interview with Professor Cermak about Professor Davenport”, Proceedings of the Engineering Symposium to Honour Alan G. Davenport for His Forty Years of Contributions, University of Western Ontario, London, Canada, June 2002.

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 1091-1102, January 1995.

Cochran, L.S., Levitan, M.L., Cermak, J.E. and Yeatts, B.B., "Geometric Similitude Applied to Model and Full-Scale Pressure Tap Sizes", Proceedings of the Third Asia Pacific Symposium on Wind Engineering, pages 917-922, Hong Kong, December 1993.

Cochran, L.S. and Cermak, J.E., "Full and Model Scale Cladding Pressures on the Texas Tech University Experimental Building", Journal of Wind Engineering and Industrial Aerodynamics, Volume 41-44, 1589-1600, December 1992.

Cochran, L.S., "Wind-Tunnel Modelling of Low-Rise Structures", PhD Dissertation, Colorado State University, Fort Collins, Colorado, 509pp, Fall 1992.

Cochran, L.S., "Influence of Porosity on the Mean and Peak Wind Loads for Three Concentrator Photovoltaic Arrays", Master of Science Thesis, Colorado State University, 1986.

Cook, N.J., “The Designer's Guide to Wind Loading of Building Structures Part 2: Static Structures”, Building Research Establishment, Butterworths Publishers, First Edition, 1990.

Cook, N.J., "The Designer's Guide to Wind Loading of Building Structures Part 1", Building Research Establishment, Butterworths Publishers, First Edition, 1985.

Davenport, A.G., “The Impact of Structural Damage Due to Hurricanes and the Prospects for Disaster Reduction”, Proceedings of Conference on Prediction and Perception of Natural Hazards (edited by J. Nemec), pages 13-21, 1993.

Davenport, A.G., "The Response of Supertall Buildings to Wind", Second Century of the Skyscraper (edited by C.S. Beedle), Council on Tall Buildings and the Urban Habitat, Van Nostrand Reinhold Company, 1988.

Davenport, A.G., "The Relationship of Wind Structure to Wind Loading", Proceedings of Conference on Wind Effects on Structures, NLP, HMSO, 1965.

Davenport, A.G., "The Application of Statistical Concepts to the Wind Loading of Structures", Proceedings of the Institution of Civil Engineers (UK), Volume 19, Paper Number 6480, pages 449-472, 1961.

Derickson, R.G. and Peterka, J.A., “Development of a Powerful Hybrid Tool for Evaluating Wind Power in Complex Terrain: Atmospheric Numerical Models and Wind Tunnels”, Proceedings of the 23rd ASME Wind Energy Symposium, Reno, Nevada, 15 pages, January 2004.

Dryden, L.H. and Kuethe, A.M., "The Measurement of Fluctuations of Air Speed by Hot-Wire Anemometry", National Advisory Committee on Aeronautics Technical Report 320, 1920.

Eaton, K.J. and Mayne, J.R., "The Measurement of Wind Pressures on Two Storey Houses at Aylesbury", Journal of Industrial Aerodynamics, Volume 1, Number 1, pages 67-109, 1975.

Federal Emergency Management Agency and Federal Insurance Administration, “Building Performance: Hurricane Andrew in Florida. Observations, Recommendations and Technical Guidance”, December 1992.

Federal Emergency Management Agency, “Protecting Manufactured Homes from High Winds TR-75”, July 1986.

Fujita, T., “Wind Fields of Andrew, Omar and Iniki”, Proceedings of the Twentieth Conference on Hurricanes and Tropical Meteorology, American Meteorological Society, San Antonio, 1993.

Hinze, J.O., "Turbulence", McGraw-Hill Publishing, Second Edition, 1975.

Holmes, J.D., “Wind Loading of Structures”, Spon Press, 356 pages, 2001.

Holmes, J.D., “Wind Loads on Lowrise Buildings - A Review”, CSIRO, Division of Building Research, Highett, Victoria, Australia, 1993.

Holmes, J.D., "Effect of Frequency Response on Peak Pressure Measurements", Journal of Wind Engineering and Industrial Aerodynamics, Volume 17, pages 1-9, 1984.

Holmes, J.D., "Techniques and Modelling Criteria for the Measurement of External and Internal Pressures", Proceedings of the International Workshop on Wind Tunnel Modeling Criteria and Techniques in Civil Engineering Applications, edited by Reinhold, T.A, pages 245-256, Maryland, USA, 1982a.

Holmes, J.D., "Comparison of Model and Full-Scale Tests of the Aylesbury House", Proceedings of the International Workshop on Wind Tunnel Modeling Criteria and Techniques in Civil Engineering Applications, edited by Reinhold, T.A, pages 605-618, Maryland, USA, 1982b.

Hosoya, N., "Wind Loads on Single and Successive Flat Plate Array Fields", Masters Thesis, Colorado State University, 1983.

Hoxey, R.P. and Richards, P.J., “Full-Scale Wind Load Measurements Point the Way Forward”, Journal of Wind Engineering and Industrial Aerodynamics, Volume 57, pages 215-224, 1995.

Irminger, I., "Experiments on Wind Pressure", Proceedings of the Institute of Civil Engineers, Volume 118, pages 468-472, 1894.

Karamcheti, K., "Principles of Ideal-Fluid Aerodynamics", John Wiley & Sons with Robert Krieger Publishing Co., 1980.

Kasperski, M., Nieman, H.J. and Goliger, A.M., “Wind Loading Aspects of Buildings in Groups: Mass-Housing Developments in South Africa”, Proceedings of the Tenth International Conference on Wind Engineering, Copenhagen, Denmark, pages 1801-1806, June 1999.

Kasperski, M., “Design Wind Loads for Lowrise Buildings: A Critical Review of Wind Load Specifications for Industrial Buildings”, Journal of Wind Engineering and Industrial Aerodynamics, Volume 61, pages 169-179, 1996.

Kernot, W.C., "Wind Pressures", Australasian Building and Contractors News", Volume 13, page 194, October 1893.

King, C.V., "On the Convection of Heat from Small Cylinders in a Stream of Fluid", Philosophical Transactions of the Royal Society, London, Volume A214, page 373, 1914.

Kopp, G.A., Surry, D. and Chen, K., “Wind Loads on a Solar Array ”, Wind and Structures, Volume 5, Number 5, pages 393-406, 2002.

Krishna, P., “Wind Loads on Lowrise Buildings - A Review”, Journal of Wind Engineering and Industrial Aerodynamics, Volume 54/55, pages 383-396, 1995.

Leicester, R.H. and Reardon, G.F., "Wind Damage in Australia: A Pictorial Review", Commonwealth Scientific and Industrial Research Organization, Division of Building Research, Highett, Victoria, 1976.

Letchford, C.W., “Wind Loads on Rectangular Signboards and Hoardings”, Journal of Wind Engineering and Industrial Aerodynamics, Volume 89, pages 135-151, 2001.

Levitan, M.L., "Analysis of Reference Pressure Systems Used in Field Measurements of Wind Loads", PhD Dissertation, Civil Engineering Department, Texas Tech University, Lubbock, Fall 1992.

Li, Q.S. and Melbourne, W.H., “Pressure Fluctuations On The Texas Tech Building Model In Various Turbulent Flows”, Proceedings of the Third International Colloquium on Bluff Body Aerodynamics and Applications, pages A9 to A12, 1996.

Mahendran, M., “Fatigue Behaviour of Corrugated Roofing Under Simulated Roof Loading”, Civil Engineering Transactions, Institution of Engineers Australia, Volume CE32, Number 4, pages 212-218, 1990.

Marshall, R.D., "The Measurement of Wind Loads on a Full-Scale Mobile Home", National Bureau of Standards, Washington DC, NBSIR 77-1289, September 1977.

Marshall, R.D., "A Study of Wind Pressures on a Single Family Dwelling in Model and Full Scale", Journal of Industrial Aerodynamics, Volume 1, Number 1, pages 177-199, 1975.

McWhirter, N., "Guinness Book of World Records", Sterling Ruth Co., 1986.

Melaragno, M., "Wind in Architectural and Environmental Design", Van Nostrand Reinhold, 1982.

Melbourne, W.H., "Wind Tunnel Blockage Effects and Corrections", Proceedings of the International Workshop on Wind Tunnel Modeling Criteria and Techniques in Civil Engineering Applications, edited by Reinhold, T.A, pages 197-216, Maryland, USA, 1982.

Melbourne, W.H., "Turbulence Effects on Maximum Surface Pressures; A Mechanism and Possibility of Reduction", Proceedings of the Fifth International Conference on Wind Engineering, edited by Cermak, J.E., pages 541-551, Fort Collins, USA, July 1979.

Monin, A.S. and Obukhov, A.M., "Basic Laws of Turbulent Mixing in the Ground Layer of the Atmosphere", Trudy Geofizs. Institute an SSSR, 2, No. 24, pages 163-187, 1954.

Okada, H. and Ha, Y.C., "Comparing of Wind Tunnel and Full Scale Pressure Measurement Tests on the Texas Tech Building", Proceedings of the Eighth International Conference on Wind Engineering, University of Western Ontario, London, Canada, July 1991.

Peterka, J.A., Cermak, J.E., Cochran, L.S., Cochran, B.C., Hosoya, N., Derickson, R.G., Harper, C., Jones, J. and Metz, B., "Wind Uplift Model for Asphalt Shingles”, Journal of Architectural Engineering, American Society of Civil Engineers, Volume 3, Number 4, pages 147-155, December 1997.

Peterka, J.A. and Derickson, R.G., “Wind Load Design Methods for Ground Based Heliostats and Parabolic Dish Collectors”, Colorado State University Report for Sandia National Laboratories, #SAND92-7009, September 1992.

Reardon, G.F. “20-Year Report”, Cyclone Structural Testing Station, James Cook University, Townsville, Australia, 1997.

Reardon, G.F. and Holmes, J.D., "Wind Tunnel Research on Low Rise Buildings", Technical Report No. 11, Department of Civil and Systems Engineering, James Cook University, Townsville, Queensland, 1981.

Richardson, G.M., Hoxey, R.P., Robertson, A.P., and Short, J.L, “The Silsoe Structures Building: Comparisons of Pressures Measured at Full Scale and in Two Wind Tunnels”, Journal of Wind Engineering and Industrial Aerodynamics, Volume 72, pages 187-197, 1997.

Richardson, G.M., Robertson, A.P., Hoxey, R.P. and Surry, D., "Full-scale and Model Investigations of Pressures on an Industrial/Agricultural Building", Proceedings of the 6th United States Conference on Wind Engineering, Houston, Texas, page B7-17, March 1989.

Robertson, A.P., Hoxey, R.P., Short, J.L., Ferguson, W.A. and Osmond, S., “Wind Loads on Free-Standing Walls: A Full-Scale Study”, Proceedings of the Ninth International Conference on Wind Engineering, New Delhi, India, pages 457-468, January 1995.

Robertson, A.P. and Glass, A.G., “The Silsoe Structures Building - Its Design, Instrumentation and Research Facilities”, Divisional Note 1482, Silsoe Research Institute, October 1988.

Rofail, A.W. and Kwok, K.C.S., "A Reliability Study of Wind Tunnel Results for Cladding Pressures", Proceedings of the First Australian Wind Engineering Society Workshop, Hunter Valley, Australia, 1991.

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.

Schlichting, H., "Boundary Layer Theory", McGraw-Hill, Seventh Edition, 1978.

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.

Schubauer, G.B. and Dryden, H.L., "The Effect of Turbulence on the Drag of Flat Plates", NACA-TR-546, 1935.

Scruton, C., "The Use of Wind Tunnels in Industrial Aerodynamics Research", National Physical Laboratories, Great Britain, NPL/Aero/411, 53 pages, 1960.

Sill, B.L. and Cook, N.J., "The Aylesbury Comparative Experiment: A Status Report", Proceedings of the 6th United States Conference on Wind Engineering, Houston, Texas, March 1989.

Stathopoulos, T., Kumar, K.S. and Mohammadiam, A.R., “Design Wind Pressure Coefficients for Monoslope Roofs: A Time Series Approach”, Journal of Wind Engineering and Industrial Aerodynamics, Volume 65, pages 143-153, 1996.

Stathopoulos, T., “Wind Loads on Lowrise Buildings - A Review of the State of the Art”, Engineering Structures, Volume 6, pages 119-135, 1984.

Surry, D. and Lin, J.X., “The Effect of Surroundings and Roof Corner Geometric Modifications on Roof Pressures on Lowrise Buildings”, Journal of Wind Engineering and Industrial Aerodynamics, Volume 58, pages 113-138, 1995.

Surry, D, “Wind Tunnel Simulation of the Texas Tech Building”, Proceedings of the Eighth International Conference on Wind Engineering, University of Western Ontario, London, Canada, page 1613, June, 1991.

Surry, D., "Pressure Measurements on the Texas Tech Building-II: Wind Tunnel Measurements and Comparisons with Full Scale", Proceedings of the 8th Colloquium on Industrial Aerodynamics, Aachen, West Germany, September 1989.

Sutt, E., Reinhold, T. and Judge, B., “Holding on to Your Roof: A Guide to Retrofitting Your Roof Sheathing Using Adhesives”, Wind Load Test Facility, Clemson University, October 2000.

Takagi, M., Nova Laboratories, Nissan Car Company, Japan, Private Communication, 1992.

Timoshenko, "History of the Strength of Materials", Dover, 1953.

Uematsu, Y. and Isyumov, N., “Wind Pressures Acting on Low-Rise Buildings”, Journal of Wind Engineering and Industrial Aerodynamics, Volume 82, pages 1-25, 1999.

Van der Hoven, "Power Spectrum of Horizontal Wind Speed in the Frequency Range from 0.0007 to 900 Cycles per Hour", Journal of Meteorology, Volume 14, pages 160-164, 1957.

von Kármán T., "The Wind and Beyond", Boston Little and Brown, 1967.

Walker, G.R., “Wind Disasters and the Insurance Industry”, Proceedings of the Eleventh International Conference on Wind Engineering, Lubbock, Texas, pages 2293-2300, June 2003a.

Walker, G.R., Private Communication, 2003b.

Womble, J.A., Cermak, J.E. and Mehta, K.C., “Internal Wind-Pressure Contributions for a Full-Scale and Model Building”, Proceedings of the American Society of Civil Engineers Structural Congress, Portland, Oregon, April 1997.

Wu, F., Sarkar, P.P., Mehta, K.C. and Zhao, Z., “Influence of Incident Wind Turbulence on Pressure Fluctuations Near Flat-Roof Corners”, Journal of Wind Engineering and Industrial Aerodynamics, Volume 89, pages 403-420, 2001.

Wu, F., Sarkar, P.P., Mehta, K.C., “Full-Scale Study of Conical Vortices and Roof Corner Pressures”, Wind and Structures, Volume 4, Number 2, pages 131-146, 2001.

Yaragal, S.C., Ram, G. and Murthy, K.K., “An Experimental Investigation of Flow Fields Downstream of Solid and Porous Fences”, Journal of Wind Engineering and Industrial Aerodynamics, Volume 66, pages 127-140, 1997.

Yeatts, B.B. and Mehta, K.C., “Field Study of Internal Pressures”, Proceedings of the Seventh US National Conference on Wind Engineering, UCLA, pages 889-897, 1993.

Yih, C.S., “Fluid Mechanics”, West River Press, Second Edition, 1988.

Keywords (index)

Wind Tunnel, Lowrise Building, Wind Engineering, Hurricane, Cyclone, Insured Losses, Wind Loads, Architectural Aerodynamics and Wind History.