Title: **Wind Engineering of Tall Buildings: Where Have We Been & Where Do We Need to Go?**

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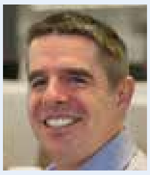
Wind Engineering of Tall Buildings: Where Have We Been & Where Do We Need to Go?



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Dr. Roy Denoon is a Principal of CPP Wind Engineering, based in Colorado, USA. He has been involved in wind engineering of tall buildings for over 25 years, and has worked on a wide range of projects around the world, from megatall towers to low-rise urban planning projects. Denoon co-authored the CTBUH Technical Guide Wind Tunnel Testing of High-Rise Buildings, is a member of the ASCE7 Wind Loading Subcommittee, and is a primary author of the soon-to-be-published ASCE Prestandard on Performance-Based Wind Design. In 2019, Denoon was made a CTBUH Fellow in recognition of his work in the field.

Abstract

As wind effects govern the design for lateral loads and responses for many of the world's tall buildings, the optimal determination of these effects is critical in the sustainable development process. The science of boundary-layer wind tunnel testing is well-established, based on synoptic wind parameters, but the influence of storm types of different temporal and spatial characteristics is still not well understood or quantifiable, despite these being the governing wind characteristics in many global locations. The determination of site-specific wind speeds and directionality and how, or whether, these should be matched to local codified values also strongly influences structural design. Design of structures for wind effects has also been conducted almost entirely in the linear elastic range, however there multiple efforts underway to develop performance-based wind design. Progress in these areas is described, along with some key challenges that must be solved before these approaches can become more widely adopted.

Keywords: Cost, Performance-Based Design, Sustainability, Wind, Wind Loads, Wind Tunnel Testing

Introduction

As the Council celebrates its fiftieth anniversary, it is a good time to look back at how wind engineering has evolved over the last fifty years. As will become clear through this paper, there have been some major advances, and some areas where surprisingly little progress has been made, despite the obvious needs. It is time, perhaps, for an industry-wide re-evaluation of the contribution of wind engineering to the success of tall buildings and urban environments and to invest in some long-overdue re-examination of some of the basic principles and approaches to design.

The Last 50 Years of Wind Engineering

Fifty years ago, wind engineering of tall buildings was in a middle ground between very simplified empirical approaches and the use of wind tunnel testing for landmark towers. At that point, it had only been a few years since the seminal work conducted on the World Trade Center Towers at Colorado State University under Jack Cermak and Alan Davenport (see Figure 1). These tests had used aeroelastic models to investigate the wind loads and responses of the towers, and pressure models to estimate the cladding design pressures. Early investigations were made into the acceptability of building motion for occupant comfort, and predictions of pedestrian discomfort at the base of the towers were made and effectively ignored (Robertson 2017).

For those not employing wind tunnel testing, codes and standards were still relatively simple documents. The British Code, CP3: Chapter V, Part 2, was published in 1972 and remained in place until the publication of BS6399 in 1995. In the United States, the ANSI standard for loads on buildings (ANSI 1972) ran to a total of 60 pages (including commentary), with 14 pages of the main standard and 10 pages of the commentary devoted to wind engineering.

The first major event held by the group that would become the CTBUH, the joint ASCE/IABSE International Conference on Planning and Design of Tall Buildings, was held at Lehigh University in 1972, and is an informative example of common industry

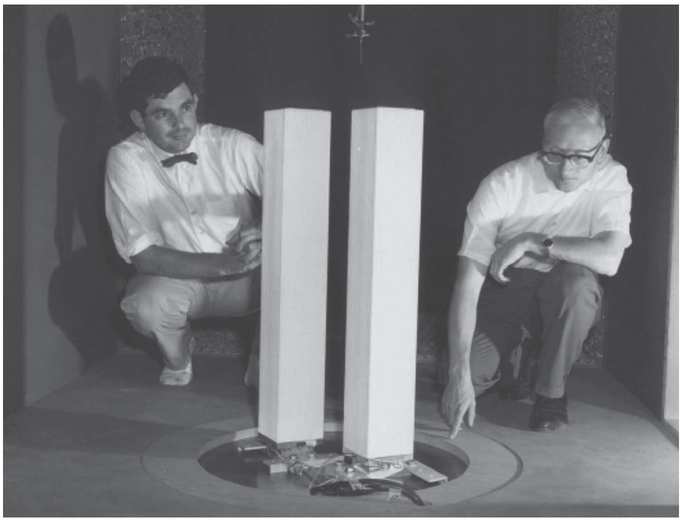

Figure 1. Alan Davenport and Jack Cermak with the World Trade Center Towers in the CSU Meteorological Wind tunnel circa 1963/1964. © CPP Wind Engineering

The effects of wind on tall buildings and tentative design criteria		
Effect	**Nature of Unserviceability**	**Recurrence rate**
Stresses in primary structure	Failure due to instability high or low cycle fatigue	<1/100,000 in 100-year-life
Forces on exterior skin	Local failure of cladding or glass	<1 per 1,000 panes in 10-year-period
Deflection of structure	Damage to architectural finishes Deterioration of performance of antennae structures	<1/100 in 10-year-period
Dynamic sway of structure	Perceptible to occupants	<1 occasion per 10 years
Windiness in pedestrian precincts	a. Uncomfortable or b. dangerous to pedestrian	a. <10 occasion per annum b. <1 occasion per annum

Table 1. Davenport's proposed wind design criteria from 1972 Lehigh Conference, reproduced for comparison against current design approaches.
Source: American Society of Civil Engineers

practices at that time. It was attended by many of the major figures in the field from around the world and provided overviews of the current state-of-the-art and their views on future research.

In the theme report on wind loading, the three key research issues identified by Davenport (1972) to improve current design methods were full-scale measurement of structural behavior, inelastic behavior and damage accumulation, and pedestrian comfort. In this report, Davenport also proposed tentative design criteria for the effects of wind on tall buildings which can be compared with current design approaches for contrast (see Table 1).

In his discussion on research areas, Cermak (1972) proposed corner modifications and "air passages" through tall buildings to reduce wind loads and responses. Cermak proposed an extensive research program into building shaping to minimize dynamic excitation and the effects of surrounding buildings and topography with the aim of having validated theoretical models for wind loading, to allow design without the need for wind tunnel testing. His goal was to achieve this within a decade. The necessity of full-scale validation was also identified by Cermak.

Melbourne's (1972) discussion of wind tunnel test expectations identified the critical importance of the correction of meteorological data to standard reference conditions. Melbourne also expressed caution about extreme value analysis when design wind loads were likely to occur during thunderstorm or tropical cyclone events due to the historical meteorological data being inadequate and the lack of knowledge about the characteristics of these types of windstorms.

Changes Over the Last 50 Years

The most obvious difference for most designers is the expansion of codes, whether this is through the provisions of the Eurocode, or the 822 pages of the current US loading standard (ASCE7-16) with 146 pages of the body and 65 pages of commentary on wind loading. A large part of these expansions has been in response to efforts to provide better design data for a wider range of building types and shapes, the recognition of the importance of surrounding terrain, and the influence of dynamic responses to wind excitation. Each of these developments has been based on wind tunnel experiments.

The basics of the boundary-layer wind tunnel, the ability to simulate different, stable boundary layer profiles using a range of augmentation techniques and testing models of a similar scale have, for the most part, remained unchanged for commercial testing of buildings (see Figure 2). The major changes have been in the model design and manufacturing processes, instrumentation, and analysis approaches. These advances have reduced the time required to complete a wind tunnel test from several months to just a few weeks. This reduction can be beneficial in limiting rework, but can also limit the positive influence of the wind engineer due to a relatively late start in the project.

Model design and manufacture has moved from the field of the artisan model-maker to the realm of the 3D design modeler and rapid prototyping manufacturing. This has been facilitated by architectural and engineering design within the 3D environment. Whereas, only a few years ago, the wind tunnel model technicians may have been the first people to build a physical model from the architect's two-dimensional plans and elevation, discovering mismatches in the drawings along the way, the architectural information received by the

Figure 2. **Typical boundary layer wind tunnel test showing pressure test and proximity models on turntable and boundary layer generation devices including trip board, spires, and floor roughness.** © CPP Wind Engineering

wind tunnel laboratory is now generally much more complete, and consistent.

In terms of instrumentation, there has been a vast increase in the number of pressure taps applied to a typical building from perhaps less than 100 to commonly more than 500. This has eliminated the need for exploratory flow visualization as sufficient taps can be incorporated into the model. The fact that all the pressures can be gathered simultaneously, has allowed the use of high-frequency pressure integration in the determination of wind-induced loads and responses. This is the second of the aerodynamic test techniques now used in place of aeroelastic testing for the majority of buildings—the first being the high-frequency balance technique developed by Tschanz in the late 1970s and early 1980s (Tschanz 1982). These aerodynamic test techniques have gained common acceptance as they are more rapid and economical to conduct, as well as being more suited to complex mode shapes than simplified linear aeroelastic models.

Increases in computational power allow faster, more complex analyses for many more wind directions than was the case in the early days of wind engineering. One of the more significant advances, and one that is often overlooked in such reviews, is the development of more statistically reliable, and robust, methods of determining site wind speeds and directionality. This runs from improved statistical fitting techniques for historical data, to the use of super stations, to the understanding of the gust response characteristics of historical anemometers to the introduction of automatic weather stations, and Monte Carlo simulations of tropical cyclone events. One thing that has not changed, however, is the reliance (in non-tropical cyclone areas) on quality basic historical wind speed data which, in some locations, can be sparse. There has also been standardization of methodologies of adjusting wind speeds and profiles for different upwind terrain conditions, largely based on the works of Deaves and Harris (Deaves & Harris 1978; Deaves 1981). The importance of accurate site wind speeds cannot be overstated in an area where for cross-wind dominated tall buildings, a difference of 10 percent in wind speeds from critical directions can result in changes in design loads of 30 percent or more.

Trending Wind Engineering Topics in Relation to Tall Building Design

Increasing numbers of tall buildings in geographical locations with temperature extremes, increasing complexity in building envelope detailing, and ever more slender buildings in very developed cities have led to a number of challenges.

In particularly hot or cold climates, stack effect, where cold air wants to descend through a building or hot air wants to rise, leads to internal pressure effects (see Figure 3). These effects can be exacerbated by, or similar effects can result solely from,

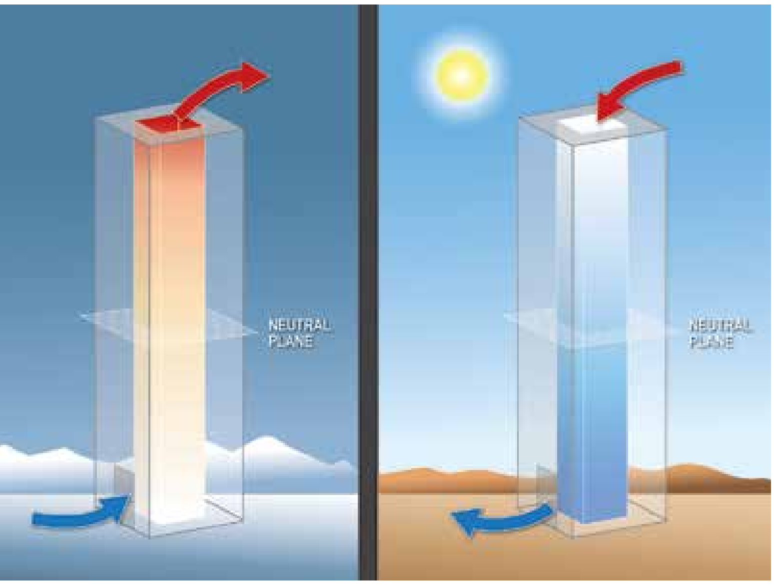

Figure 3. Schematic illustration of stack effect. © CPP Wind Engineering

Figure 4. Sample of porous cladding being tested for noise in the wind tunnel. © CPP Wind Engineering

openings in the building envelope such as outdoor terraces at upper levels of the building. These pressures can cause issues with door operability, affect elevator operations, or cause noise inside the building.

Other sources of wind-induced noise in newer buildings include partition noise from detailing of stud connections as a result of building sway, and wind noise from external detailing. External features that have been observed to cause noise include sunshade features and the porous metal panels (see Figure 4) that are often used to provide screening around rooftop mechanical equipment.

With very slender buildings of small cross-sectional dimensions and extreme aspect ratios, serviceability accelerations are often the governing criteria. These accelerations are entirely resonant in nature and are most often, in this type of building, a vortex-shedding (cross wind) response. As such they are very sensitive to building shape, structural properties, and wind speed. The most common ways to mitigate accelerations are by modifying building shape. In one example, it was possible to reduce accelerations by more than 50 percent in this manner (see Figure 5). Adding supplementary damping devices is another effective method.

Building shaping can often be effective but can be limited by project or site constraints. The appropriate type of shaping is also dependent on the site wind climate (Denoon et al. 2012). Supplementary damping devices can be either tuned to specific modes of vibration of interest, or distributed untuned devices can also be used.

The most commonly used set of acceleration guidelines (and this author will refer to them as guidelines rather than criteria) internationally are slightly controversial. ISO10137 (1997) was introduced to follow ISO6897 (1984) and made two significant improvements by moving the guidelines to a one-year return period (instead of five years) and using peak accelerations (rather than standard deviation) as its basis. ISO6897 was based on field measurements and extrapolations from real buildings and structures, in some of which there had been complaints and in some of which there had not.

The author has a copy of the original hand drawn graph on which this was based and, from other papers by Andy Irwin, it is possible to ascertain that there was no obvious difference between residential and commercial buildings. ISO10137, however, chose to make this differentiation and while the office guidelines match reasonably well with ISO6897, when corrected appropriately, the residential guidelines are significantly more stringent. Indeed, unpublished notes from the preparation of the standard indicate that the Japanese Working Group, suggested that "estimated results of acceleration on actual buildings using structural performance estimated with observation values indicated that about 1.5 times the basic assessment curve for residence seems appropriate to the basic assessment curve for office."

What is agreed between senior wind engineering practitioners is that the ISO10137 residential guidelines can be very hard to meet, and a huge number of existing tall residential buildings that have not developed high complaint rates exceeded these values in their design predictions. This must lead to questions about whether supplementary damping is consequently being over-specified. What is needed is a more open dialogue between designers and building owners/tenants in setting appropriate acceleration performance targets with knowledge of the financial implications of that choice.

Another, very commonly asked question is that of the effects of global warming. Global warming's significance for extreme wind speeds will be dependent upon the storm type. For locations where wind speed analyses are based on historical data analyses, it may be many years before reliable assessments can be made. For tropical cyclone regions, conclusions may be drawn earlier, with Hurricane Michael in 2018 already showing indications that windstorm models may need to be revised. Elsewhere in wind climate analysis, increased use of mesoscale atmospheric modeling in the prediction of, particularly, upper-level wind speeds at locations where there is limited field data to hand can be anticipated.

A bigger issue in many locations, however, is the use of excessively conservative design wind speeds as mandated by local authorities. This can lead to a massive overuse of materials and increased construction costs. In fact, one major developer based in a location with a mandated strength design wind speed around 20 percent above best estimate values has estimated their construction costs have been inflated by over US$1 billion over the last few years. At times, decisions on local design wind speeds can be based more on opinion or perceived experience rather than (as they should be) statistical analyses conducted by suitably qualified professionals.

Computational Wind Engineering (CWE) using Computational Fluid Dynamics (CFD) tools is often promulgated as a replacement for boundary layer wind tunnel testing. When well-conducted, and validated, CWE is now at the stage where it can be used in the reliable prediction of pedestrian wind comfort. For this purpose, it has advantages in being able to show a more complete picture of the variation of wind comfort around a development than is always possible with the discrete points from a typical wind tunnel test. It is, though, still limited in the prediction of the extreme gust events that may control pedestrian safety.

While CWE can be successfully used in ground-level wind speed studies, it is not yet sufficiently developed in its accuracy and speed to replace the wind tunnel for loading and response studies. Indeed, it is probably another decade or two at least (the same time frame that has been predicted since the introduction of CFD to wind engineering in the mid-1970s) before it can be reliably used to replace the analog flows modeled in the wind tunnel. It should also be cautioned that CWE results can frequently look impressive and convincing but, like any engineering calculation, are only as good as the input parameters. And, it takes experience within the field of wind engineering to be able to both define these parameters and interpret the validity of the output.

Performance-based wind design (PBWD) is at the start of codification with a prestandard on the subject published by ASCE (2019). This prestandard follows the adoption of non-linear analysis techniques in the field of seismic design. There has, to date, been relatively little research into this area within wind engineering, and the provisions of the prestandard will undoubtedly be open to (hopefully constructive) criticism following its publication. One particular point of interest is to compare the performance objectives and acceptance criteria with those suggested by Davenport (1972). While there are some reasonably comparable values, the ultimate limit state objectives can be interpreted quite differently.

One very likely outcome from PBWD developments is the integration of distributed time histories of wind tunnel data directly into structural design models. This is an approach that has been used for a number of years for long-span roofs in order to calculate maximum load effects in primary members. For tall buildings, however, the standard approach has been

Figure 5. SRG Tower, Dubai—an example of building shaping being used to reduce response. © Killa Design

to maximize load effects at the base and distribute the loads up the building accordingly. To optimize the structural design of many tall buildings, especially for those where there are changes in the structural system with height, it can be extremely valuable to maximize loads at different critical locations or in key elements. This, though, is not as simple a task as it is in the seismic realm where there is unidirectional excitation at the base.

In wind engineering, there is multi-directional, uncorrelated excitation that varies with height; the effects of all possible wind directions need to be accounted for, as do the potentially non-monotonic variations of loads and responses with wind speed. And this all needs to be done on a statistical platform based on a directional wind climate model to ensure that the correct performance goals are being met. A subcommittee of the ASCE7 wind loading group is currently working on initial design studies into PBWD using generic buildings in a selection of wind climates.

Where Has the Field Failed to Progress Significantly?

What is clear from the discussion herein is that, even though significant advances have been made, many of the future research areas identified in 1972 by the doyens of the field remain under-investigated.

In particular, there has been very little effort to gather data on thunderstorm structure and temporal characteristics so that the influence on tall building design can be assessed. Given what is known about the outflow characteristics of thunderstorms, it is to be expected that they will have very different effects on the wind loading and responses of tall buildings (see Figure 6). Firstly, the peak wind speeds normally occur at lower heights (between 50 meters and 150 meters) with a correspondingly smaller lever arm on supertall buildings than for classical boundary layer profiles. The peak wind speeds also tend to occur for a relatively short period of time and are often associated with a change in wind direction (see Figure 7). This limits the potential to generate correlated excitation over large extents of the building for long enough periods to develop large cross-wind responses and hence the loads and accelerations can be expected to be significantly smaller. While some experimentation has been done in wind tunnels to simulate the effects of thunderstorms on tall buildings, this has mostly been based on matching assumed profiles, but not the temporal characteristics. As such, it is of limited value for designers, compounded by the fact that there is still very little reliable field data of thunderstorm structure on which to build a statistically reliable approach to predicting their characteristics.

It is not only field measurements of windstorm characteristics that are in short supply. As identified by many of the attendees at the Lehigh conference, the industry needed, and still does, more field verification of actual building responses to wind excitation. Without this, it is difficult to assess the reliability or conservatism associated with current practices. Measurements need to consider the as-built structural properties (which can be difficult to measure or extrapolate to larger amplitudes) as well as the responses to real windstorms. The results need to be shared publicly, with open discussion of variances from design predictions.

While design for performance of tall buildings under wind excitation has progressed a lot over the last 50 years, especially in terms of reliability performance goals, there has been little to no work to statistically investigate how that reliability might change over the lifetime of a building. While standards such as ASCE7-16 mandate lower bounds for wind tunnel results in comparison with code estimates to ensure that reliability is not compromised by the removal of adjacent buildings,

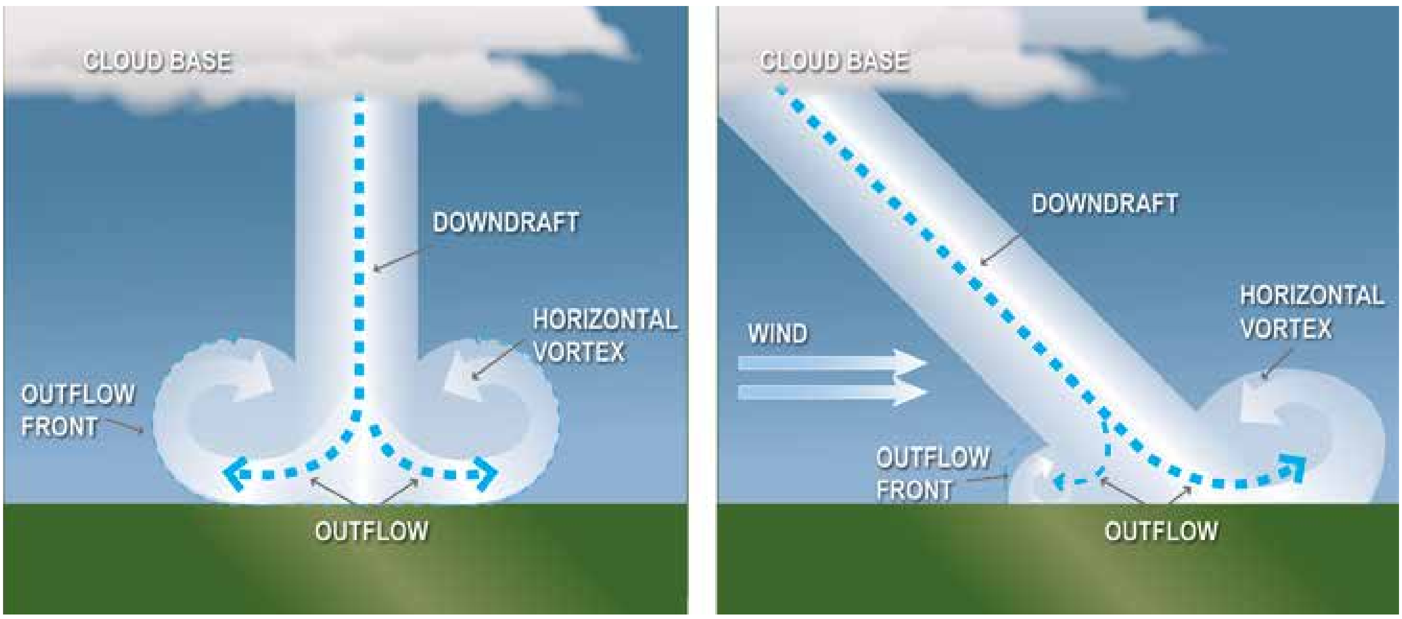

Figure 6. Schematic of thunderstorm outflow. © CPP Wind Engineering

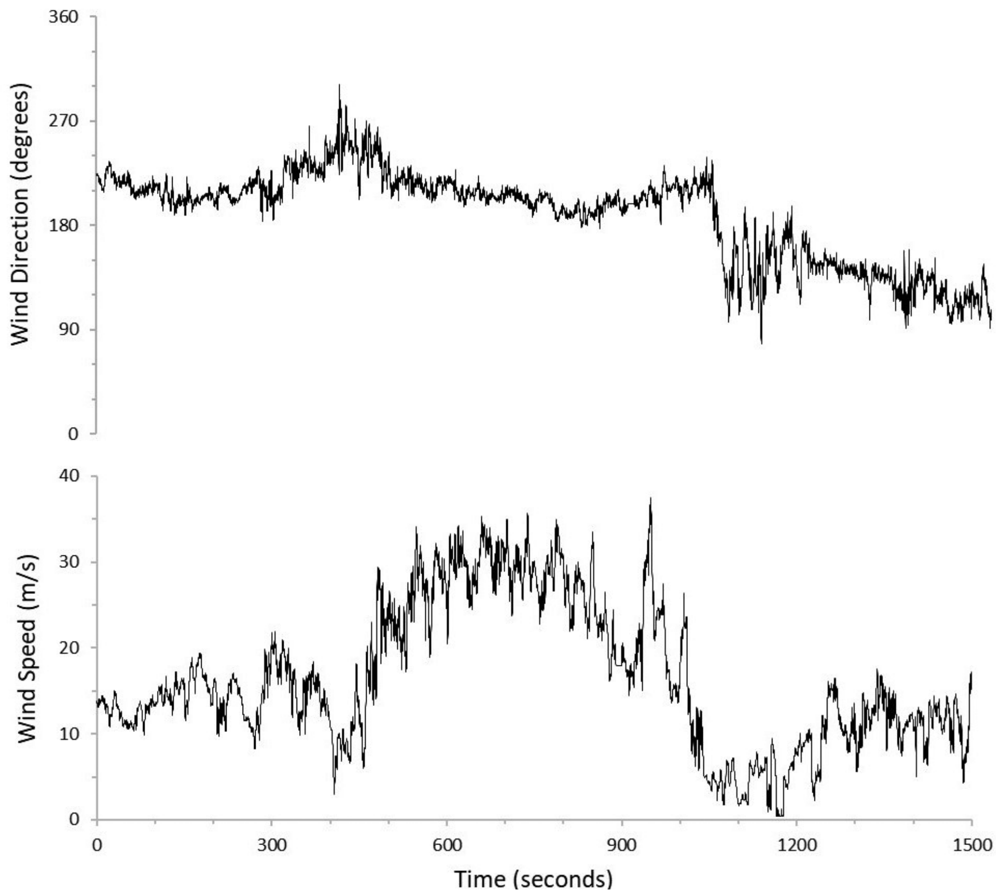

Figure 7. Measured time history of a thunderstorm: with wind direction (upper) and wind speed (lower). © Roy Denoon

little has been done to investigate the likely effects of future developments on buildings. In the majority of cases within a dense urban environment with many similar buildings, future development will probably increase shielding and the removal of adjacent buildings is likely a temporary condition. However, for buildings taller than their neighbors, construction of new projects of similar heights can have significant detrimental effects.

Progressing the Field of Wind Engineering to Address Industry Needs

In many ways, industry needs are not being well served by academic research or project-specific commercial studies for numerous reasons. Firstly, there are relatively few wind engineers to lead relevant research and development projects. Those in the consulting practice are often time- and budget-constrained as the development and construction industries have increasingly begun to view wind tunnel testing as a commodity product. This leaves little room for valuable investigations that go beyond the contracted scope of work. In the academic sphere, success is often measured by publication rate. For major wind engineering studies, particularly those involving field measurements, it can take a long time to produce important work that may not be reflected in a large number of publications.

As noted above, developers should have a strong financial interest in optimized wind engineering, whether that is from setting design standards to having competently conducted wind tunnel studies. Wind engineers have typically not been effective in selling the value of their work, partially as a consequence of there not being a good benchmark on most projects on which to calculate construction or lifecycle cost savings. There needs to be a more open dialogue between all members of the design team, and appropriate investment from the beneficiaries of this work. Perhaps the development of PBWD techniques will drive this. Perhaps it will be driven by increases in construction costs that increase the value of efficient design. In any case, it cannot be left to the enthusiasm of wind engineering specialists in their spare time, as is the case for many current efforts.

Conclusion

Wind engineering has clearly progressed a long way in the last fifty years. However, in many areas it has stagnated. It is proposed that now is an appropriate time to re-evaluate some of the basics and push for funding to address real research needs, many of which have not changed fundamentally since being identified at the Council's first conference in 1972.

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