FUTURE DIRECTIONS IN WIND ENGINEERING

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Introduction

At the request of the organisers of AWES10, I have been asked to gaze into a crystal ball and look at where wind engineering, as a discipline and a profession, is going in the 21st Century. This is, of course, not an easy task, but if one pitches predictions far enough in future, no one will be around to question the accuracy of the predictions. On the basis that wind engineering as we know it know is about forty years old, I will attempt to look forward to the next forty years.

The name 'wind engineering' was coined originally by Jack Cermak in about 1979, although it really started as a defined discipline in about 1960. However, despite its youth, in Australia, apparently it is regarded as a 'mature discipline' by those responsible for dispensing research grants.

Although structural analysis has probably reached a plateau of development, to the extent that now every practising structural engineer has state-of-the-art finite element software at his fingertips, that should enable him, or her, to predict internal forces and moments with great apparent accuracy, there are good arguments that structural loading estimation, including wind loading, has not reached anything like the same level of precision.

In this presentation, I will first summarize what I see as the major milestones from the last forty years, before suggesting some directions for research activity for the next forty.

Major milestones in the first forty years

The foundations of modern wind engineering were firmly set in the early nineteen-sixties. Several papers in the 1st International Conference on Wind Effects on Buildings and Structures at Teddington,U.K. in 1963 (effectively ICWE1) set the scene for the next forty years. Some examples of the directions set at this conference are :

- The adoption of Gumbel's extreme value analysis for design wind speeds by Shellard [1].
- The description of the turbulent atmospheric boundary layers in synoptic winds, including the concepts of spectra, correlations and gradient wind speeds, by Davenport [2].
- A description of an early attempt at full-scale pressure measurement on a full-scale building, using 'home-made' electrical pressure transducers, by Newberry [3].
- The modelling of the atmospheric boundary layer in a wind tunnel (in Denmark) with a long fetch of surface roughness, described by Franck [4] (although this work was primarily led by Martin Jensen).
- A description of the principles of aeroelastic modelling of structures in wind tunnels by Whitbread [5] and Walshe [6].
- The basic theory of the buffeting of structures by atmospheric turbulence using random process and vibration theory by Davenport [7] and Harris [8].
- Selberg's [9] empirical formula for the flutter speed of suspension bridges, (this formula is still in use today).
- The description of the principles of galloping instability by Parkinson [10].
- An exposition by Scruton [11] of the mechanisms of cross-wind vibrations of slender structures by vortex-shedding, including the phenomenon of lock-in, and the use of helical strakes.
- A random excitation model of vortex shedding by Nakagawa et al [12], following earlier work by Fung.

- A description of the first 'modern' wind loading code, with design wind speeds based on a statistical analysis, height-dependent velocity profiles, 'shape factors' derived from boundary-layer wind tunnel tests and dynamic effects; the draft Danish Code was described by Jensen [13].

The above papers were ground-breaking and read well, even today. One wonders in fact whether some of them would even be published in 2003, if submitted for publication today! It seems incredible that there were only 24 papers presented in total at the Teddington Conference – at least 13 of these (as listed above) were highly significant the time – more than half the total ! It is also interesting to note that, although there were only 24 papers presented, about 300 persons attended the Conference, of which more than half were practising engineers from industry.

Although, not represented at the Teddington Conference, at about the same time, Jack Cermak in Colorado was developing the first large boundary-layer wind tunnels. Later in the nineteen sixties, one of these wind tunnels was used for the first detailed wind engineering study of high-rise buildings – of course, these were the World Trade Center Towers in New York.

Scanlan [14] introduced his empirical flutter derivatives for bridge decks in the late sixties.

Such was the explosion of interest in the field created in the sixties, that in the next two decades wind engineering research was largely a continuation and reinforcement of the work described above.

However, some new features of the work of the nine-seventies and –eighties, worth noting are listed below :

- The development of large boundary-layer wind tunnels in the 70's. This includes the construction of the wind tunnels at Monash, Sydney and James Cook Universities in Australia. All three of these are still operating. The first two were constructed primarily for commercial wind-tunnel testing of tall buildings.
- The continuation of full-scale measurements – the interest in this was shown by the special conference on the subject held at London Ontario in 1974 [15]. The most comprehensive of the studies of the seventies were the Aylesbury full-scale measurements by B.R.E. (e.g. [16]), and the measurements on the Commerce Court by the N.R.C. of Canada (e.g. [17]). In the nineteen-eighties this was continued with the Silsoe Structures Building in the U.K., and the Texas Tech Field Experiment in the U.S.
- Work on wind flow over hills and topography, which was inspired by the interest in wind energy in the seventies. The theoretical work of Jackson and Hunt [18] put these studies on a firm theoretical basis.
- A strong interest in preventing wind damage particularly on small low-rise buildings, initiated by such events as the Lubbock tornado of 1970, and Cyclone 'Tracy' in Darwin in 1974.
- Development of Monte Carlo simulation methods for prediction of extreme wind speeds in rare events such as tropical cyclones.
- Major revisions of the wind loading codes and standards in several countries.
- Studies of internal pressures in buildings that had been ignored previously (e.g. [19], [20]).
- Significant incremental developments in wind-tunnel instrumentation – examples of this are: development of high-response tubing systems for fluctuating pressure measurements, cheap solid state pressure sensors; multi-channel electronic scanning systems; the high-frequency force balance for high-rise building studies. These developments have been accompanied by increased post-test computer processing of data
- The identification of thunderstorm 'downbursts' by Fujita [21]

The nineteen-nineties introduced some important new development areas into wind engineering :

- Computational Wind Engineering. This is an area which showed great promise at the start of the nineteen-nineties but had failed to achieve its potential by the end of that decade.
- Complex damage models from catastrophic events such as hurricanes, for insurance and re-insurance companies and government agencies. Much of this work however has been privately funded and is not available in the public domain.
- Thunderstorm research by wind engineers, following the recognition of the importance of these events for extreme winds in many countries. This work started slowly and is just now gaining momentum.

The late eighties and nineteen-nineties were also notable for the rise and rise of commercial wind tunnel operators. The disconnection of commercial wind tunnel operations from research groups, has the danger that innovation will be stifled in the interest of meeting immediate deadlines and the need to turn a profit. However, the North American situation has shown that competition in the marketplace, will induce the commercial operators to innovate. Therefore, I don't see this trend as being worrisome.

However, a bigger worry is the commercialisation of the publication of wind engineering research and the incredible proliferation of papers on the topic in the last few years. As an example, the Journal of Wind Engineering and Industrial Aerodynamics published 134 papers in Volume 90 in 2002. There is one other journal dedicated to wind engineering, and several others which publish papers on the topic (not including specialist wind energy journals). Thus, there were probably 200 papers on structural-related aspects of wind engineering published in journals last year. How many of these were of real significance compared with the very high percentage of significant work published at the original Teddington Conference ?

However, I don't believe that topics for real innovative research in wind engineering have been exhausted. I would like to discuss some of these in the remainder of this paper.

<u>The wind loading 'chain'</u>

The wind loading 'chain' of Alan Davenport, [22], forms a useful basis for considering the areas that most need study to better describe the phenomenon of wind loading of structures. A version of this is reproduced in Figure 1.

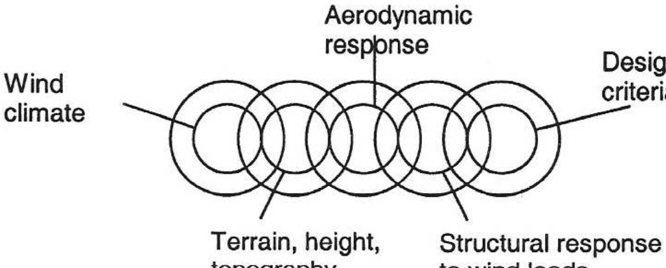

Figure 1. The Wind Loading 'Chain'

Each link in the 'chain' is essential to the whole process, and a weakness in one link will result in a weakness in the whole chain, i.e. lack of knowledge in any one area, means that the definition of wind loading, in general, suffers.

The elusive thunderstorm

The first element of the wind loading chain is the wind speed itself. Putting the 'wind' back into 'wind engineering' should be a priority for the 21st Century. Until recently there was a tendency to assume that we understand all that we need to know about wind storms, their origins and characteristics. This is far from the truth. A good example is extreme winds produced by thunderstorms. It is becoming clearer and clearer that at many places in the world, severe downdrafts from thunderstorms are the either a significant contributor or, in fact, the dominant contributor to the extreme wind climate, for the risk levels, or return periods, applicable to the design of most structures.

This work will require full-scale measurements, that can be both frustrating and time consuming. However, the availability of automatic weather monitoring stations means that such measurements are no longer expensive.

One of the big uncertainties with thunderstorms is the vertical wind profile,and the vertical extent of the layer of high speed air that occurs in these events. This will require masts of 100 metres or higher. Such measurements are in progress in Texas and Singapore, but not in Australia.

The simulation of thunderstorm 'downbursts' in wind tunnels will continue to be pursued and move from the small 'pilot' scale, to larger simulation facilities. There are already plans for a large facility of this type at the University of Western Ontario.

Type I or the G.E.V. ?

There is currently considerable debate in the journal literature as to the 'correct' extreme value distribution for extreme winds, and, in fact, also for other meteorological variables. There is strong opinion being expressed by some (but by no means all) statisticians, and some wind engineers, that the traditional two-parameter Type I (Gumbel) Distribution is the 'right' distribution, and that attempts to introduce the more flexible three-parameter Generalized Extreme Value Distribution (which of course includes the Type I as a special case, with a fixed shape factor of zero), should be resisted.

The arguments used in this debate address the following issues :

- The underlying parent probability distribution of wind speeds
- The existence, or not, of an upper limit to extreme wind speeds
- Sampling errors associated with estimating shape factors

The arguments and counter-arguments to the above issues have been expressed elsewhere. However, it needs to be remembered that all probability distributions are convenient empirical fitting functions for making predictions (either interpolations or extrapolations) based on existing recorded data. Hence the greater flexibility of a three-parameter distribution over a two-parameter one offers considerable advantages. Extreme value prediction has had relatively less innovative research in the field of extreme windspeed prediction, than has occurred in other geophysical fields such as flood prediction, and offshore wave height modelling, in the last couple of decades. Wind engineers can learn a lot from workers in these other fields who have introduced new analysis and prediction techniques.

Prediction of extreme wind speeds is an essential part of the first link in the wind-loading chain. Keeping up-to-date and improving extreme value analysis techniques will be important over the next few decades.

Climate change and the effect on design wind speeds

The evidence of increasing ocean temperatures and water level rises in the atmosphere in the last hundred years, is now providing fairly convincing evidence that climate change due to human activity is having an effect on the world's weather. We are currently in the midst of the worst drought in 100 years in Australia, and some of the worst bushfires in living memory in south-eastern Australia, and there are claims that the el-Nino and el-Nina cycles are being modified by Greenhouses gases.

So what are the ramifications and opportunities for wind engineering of all this? Firstly, what is the effect on design for extreme wind speeds. Clearly, tropical cyclones, which require a minimum sea water temperature of around 26° for existence, are likely to be more common over the tropical oceans. On the other hand, there may well be re-direction of warm water currents, so that some locations may see fewer cyclones rather than more. Some of these questions will be addressed by atmospheric scientists and mathematicians with large-scale atmospheric models. Wind engineers need to monitor this work which will affect long-term wind prediction for return periods of the order of 500 years, for structural design for ultimate limit states.

The other main extreme wind in Australia is severe downdrafts associated with thunderstorms. This is primarily an over-land phenomenon driven by atmospheric convection, and probably will be less affected by climate change.

There is already a strong belief in the insurance and re-insurance industries that climate change is associated with the large increase in insurance losses caused by synoptic winds in the last couple of decades. The jury is probably still open on this question, with some disagreement amongst meteorologists on the cause of the recent high winds in Western Europe.

In summary, wind engineers need to take more interest, and perhaps involvement, in the prediction of climate change on design wind speeds. The statement in the the Commentary to AS/NZS1170.2:2002 that 'The Standard does not attempt to predict the effects of possible future climatic changes, as the evidence for changes in wind speeds is inconclusive' will need to be reviewed and revised, for the next edition. Structural engineering will expect some guidance on this question. For tropical cyclones, in particular, this will require the revival of simulation of tropical cyclone wind speeds in Australia, as discussed in the following section.

The need for better design wind speeds in Regions C and D

The new Australian/New Zealand Standard on Wind Actions has two new factors, F_C and F_D, applicable to the Regional Wind Speeds in the cyclonic Regions C and D in the Standard. These were introduced due to uncertainty in the appropriate design wind speeds for these Regions. In the nineteen-seventies and early nineteen-eighties, Australia was a leading player in the development of Monte Carlo techniques for extreme wind prediction. These methods use satellite data on cyclone tracks, and eye structure, to form the basis of a probabilistic simulation model of tropical cyclones that enable predictions of their effects including extreme wind speeds to be made. Although the technique continues to be used for storm surge prediction, it has not been used for wind prediction in this country, for more than twenty years.

On the other hand, in the United States, the situation is quite different. This technique has been further developed, and is now the basis for the design wind speeds in the American Standard ASCE-7 along the coastlines of the Atlantic Ocean and the Gulf of Mexico, which are of course affected by hurricanes, the Northern Hemisphere version of tropical cyclones.

The recent work in the U.S. ([23], [24], [25], [26]) incorporates improved wind-field models for hurricanes – now based on fluid-mechanics prionciples, and less on empirical probabilistic models, and allowance for the weakening of storms as they cross the coastline.

It is overdue for Australia to get back into this activity, with updated models, rigorously calibrated against recorded data for those stations – primarily in Western Australia - where this can be done. These simulations should incorporate the effect of wind directions. There *are* directional effects on wind loads in Regions B, C and D, and we are currently penalising designers by not including them.

The next decade will also bring bring improved information on the profiles of wind speed with height in tropical cyclones and hurricanes,through measurements by sonic radar 'profilers' and drop-sonde measurements. Information already available shows that the profiles in the eye-wall regions are not very similar to those measured in the outer regions of tropical cyclones, or in larger extra-tropical synoptic systems.

Wind-driven debris – the forgotten load

It is well-known that impact on buildings by wind-driven debris does as much, if not more, damage in severe wind storms, such as tropical cyclones, thunderstorm downbursts and tornadoes, than does direct wind pressure. However, the amount of published literature on the topic is miniscule, compared with the several thousand on direct wind loading. Test criteria for flying debris impact seem to have been developed with little understanding of the mechanics of flying debris, and are often very conservative as a result.

Although there have been few excellent *unpublished* studies in this area, particularly in the United States for insurance companies and the like, especially related to tornadoes, and some recent excellent work in the U.K. [26], this is quite an open field for research, with opportunities for study in the following areas :

- Basic aerodynamic coefficients of generic debris types
- Trajectory models – both deterministic and probabilistic
- Impact models and energy transfer
- Improved test criteria

Database design

Moving now to developments affecting the third and fourth links of the wind loading 'chain'....

A long-term project in North America (where wind engineering research continues to be strongly supported) is the development of databases of time histories of wind pressure coefficients on generic low-rise buildings, generated primarily from wind-tunnel models. These are stored on CDs or DVDs (and possibly later on web sites) and made publicly available. Although the stated intention is to make this information available to structural designers, it is more likely that the information will be used by code-writers and researchers.

Accumulation of this data commenced at the University of Western Ontario in 1997 with measurements on four low-rise configurations, all with roof slopes of 1:24 (about 2.4°) and each with simultaneous measurements from 500 pressure taps at five degree direction intervals. These taps covered about half the surface area of walls and roof at close spacing. More recent measurements have been made on many other configurations with even more pressure taps covering the complete building surface.

The information in this data obviously provides everything necessary to determine wind loads on both cladding and structure, and including both extreme loads and fatigue time histories. However only a very small fraction of the data is significant from the point of view of design, and a challenge for researchers is to reduce the data to a more usable size.

Australian and New Zealand wind engineers could potentially contribute to the project in two ways:

- Contributing to the data base
- By analysing and processing the publicly-available data from North America

To contribute to the database, a laboratory would need state-of-the art pressure measurement instrumentation with up to 1000 channels of simultaneous pressure measurement, so this is not an option for most laboratories in the short term. However the second option is feasible and can be done right now.

This project is organised and funded by the National Institute of Science and Technology in Washington, D.C.

<u>Computational wind engineering – does it have a future?</u>

The early applications of Computational Fluid Dynamics to wind engineering took place in the late nineteen-eighties. One of the earliest studies was that of David Paterson at the University of Queensland [28]. At the start of the nineteen-nineties, computational wind engineering (CWE) was the new growth area of wind engineering. There have been three International Conferences on the topic since 1992. However, the growth in the field has definitely slowed now. So what has happened?

Firstly many of users in the field have used commercial Computational Fluid Dynamics software which are usually based on the Reynolds Averaged (mean flow) Navier-Stokes equations with simplified turbulence models of the k-epsilon type, or developments of them. This type of model reproduces the mean flow in ducts and boundary layers quite well, but performs badly in stagnation flows and separated flows. Thus it can reproduce quite well atmospheric boundary-layer flow over shallow hills, but not flow around bluff bodies such as buildings.

Large-eddy simulations (LES), on the other hand, solve the time-dependent equations of motion for the larger scales, while modelling the smaller, sub-grid, scales. The computing requirements for this type of simulation, for real three-dimensional problems, are beyond most people at the present time, however.

An excellent review of the state-of-the art in CWE in 1999, was given by Murakami and Mochida [29].

I suspect we will see slow, incremental growth in LES solutions in CWE over the next few decades, as computing power, and parallel processing continues to expand. There is also a chance that totally new mathematical or numerical approaches to the solutions of the equations of turbulent fluid flow will be developed in the next few years, and revolutionize the field.

<u>Architect-driven wind engineering</u>

Structural engineers and wind engineering will continue to be challenged by architects with exotic shapes for the roofs of sports stadia, and tall buildings. The latter will, no doubt, continue to grow taller, and break new height limits.

Wind tunnel engineers will be challenged to develop new measurement techniques for the overall wind loads and response of these structures. It is likely that for most structures these will be based on multi-channel simultaneous pressure measurements, as these measurements contain all the required loading information for any structure, including the contributions to the loading from resonant effects. Some structures with open framing or porous surfaces however, are not amenable to pressure measurements, and force based techniques will continue to be required. The challenge will be to process the huge amounts of data generated by the multi-channel measurement systems, and to provide useful and usable reduced data for structural engineers, including distributions of equivalent static loads for mean, background and resonant components of the loading

Multi-hole pressure probes will probably replace hot-wire and hot-film anemometers for most flow measurement situations in wind engineering, including ground level measurements for pedestrian winds.

The 5-kilometre suspension bridge

The longest suspension bridge at present (Akashi Kaikyo) has a main span of 2 kilometres and overall length of 4 kilometres. Overall suspended lengths of 5 kilometres, and main spans of 3 kilometres are being proposed. The structural design of such super-long suspension bridges are totally governed by aerodynamics, and flutter speeds in particular. In Japan, many deck geometries have been studied – most of these involve vented or split deck arrangements. Improving the aerodynamic stability of super long-span bridges will be an ongoing activity for the next few decades.

The length of cable-stayed bridges is governed not by deck flutter but by wind- and wind-rain induced vibration of the supporting cables. No doubt the ongoing study of this phenomenon and its mitigation will also keep bridge aerdynamicists busy in the coming years.

The future for wind codes and standards

Wind loading codes and standards represent the major interface between structural and wind engineering, and the last link in the wind loading 'chain'. In the last forty years, the major wind codes and standards have developed in different directions. There is now a trend towards alignment of national standards. In Europe, the structural Eurocodes have had a lengthy and somewhat painful pregnancy, but the the Eurocode 1 Part 1.4 Wind Actions is close to birth. The Australian and New Zealand Standard on Wind Loading is now fully aligned. In North America, there is a move to align more closely the wind loading rules of the National Building Code of Canada with the American Standard, ASCE-7. The ISO working group responsible for the ISO Standard has now reconvened, and is working towards revision of ISO 4354. The International Association for Wind Engineering has organised two Workshops on International Codification for Wind Loads, and a special session is planned on the topic at ICWE11 later this year. However, the alignment of loading standards is looking like a slow process with wind engineers playing a fairly minor role, even for wind loading standards.

The chances of the world will be using a single wind loading standard in ten, or even twenty, years from now are quite small – however it is possible that this may be achieved in thirty or forty years. A more likely outcome is that there will be two or three international model standards, and national or regional building codes will reference one or other of these documents. Australia and New Zealand should continue the process of alignment of wind loading rules with other countries in the Asia-Pacific and North America, as well as the ISO involvement

Wind Energy

A major trend in the 21st Century will be the expansion of wind energy. This is being driven by the Kyoto Protocol on Greenhouse Gas Emissions. Although Australia has not yet signed this Protocol, it will eventually be forced to do so.

Australia (unlike New Zealand) is a late starter in the development of wind energy and the installation of wind turbines. However, this field is now quite active with most States having projects in this area. Wind turbines are now moving from the small 'back-yard' private scale projects, to large scale industrial-sized projects.

The southern coastline, and Tasmania, are the most prospective in Australia, with a project by a major private sector company to install 120 wind generators in the vicinity of Portland, Victoria [30, 31]. Also in Western Australia, Western Power is expanding its longstanding pilot project at Esperance.

There are opportunities for wind engineers here in the specification of site-dependent factors for height terrain and topography, and in the development of design criteria for extreme wind loads on wind turbines and their supporting towers, that are invariably sited in very exposed positions.

Conclusion

After reviewing the state of the subject forty years ago, I have attempted to forecast for the next forty years.

Whatever the outcomes, we should at least expect to have 40 more years of extreme wind data to analyse in forty years time....!

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