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Wind Engineering Studies of Bridges (see p. 9)

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EMERGING ISSUES IN WIND ENGINEERING - PART 2

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(*From the Editor: This is Part 2 of a paper presented during the 11 ICWE. Part 1 was published in July 2003 issue of The Wind Engineer)*

3 SOME EMERGING ISSUES

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 windstorms, their origins and characteristics. In fact, it was assumed that all extreme winds were large-scale synoptic winds, with boundary-layer characteristics remarkably similar to those found in boundary-layer wind tunnels! 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 occur often enough to be 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. Figure 1 shows that this is certainly the case for west Texas, and Lubbock. Annual maxima from thunderdays control the combined distribution for return periods (mean recurrence intervals) greater than about five years.

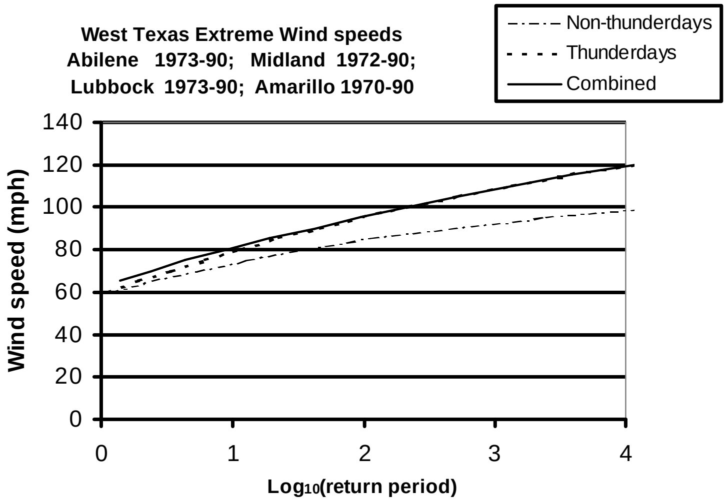

Figure 1. Extreme wind gust analysis for four West Texas stations combined

Defining the structure of these events will require extensive full-scale measurements, this will be both frustrating and time consuming. The events are of short duration (Figure 2), and usually do not effect large areas. However, the availability of automatic weather monitoring stations means that such measurements are no longer expensive. An impressive example of the measurements that are possible is the 1-mile profile of thunderstorm downdraft that was obtained at Lubbock on June 4, 2002 presented in this Conference (Figure 3).

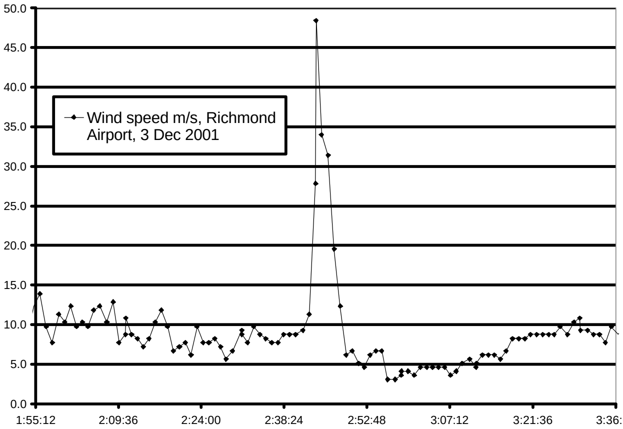

Figure 2. Time history of wind speed in a downburst near Sydney, Australia (plotted by Richard Weller from data recorded by Bureau of Meteorology)

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 at Texas Tech, and Edmund Choi presents some data from Singapore in this Conference.

The simulation of thunderstorm 'downbursts' in wind tunnels will continue to be pursued and move from the small 'pilot' scale (Figure 4), to larger simulation facilities. There are already plans for a large facility of this type at the University of Western Ontario. There is also some interesting simulation work at Texas Tech, with moving and pulsed jets, under the direction of Chris Letchford.

Tornados are major events associated with thunderstorms. Simulation of these, both numerically and experimentally, at laboratory scale is a research area that is re-emerging. Again, Chris Letchford and Darryl James at Texas Tech are at the leading edge of this work.

Studies of the non-stationary dynamic response of tall structures to downbursts and tornados is the subject of some papers at this Conference. Measurements of time histories of wind speed fluctuations over the height of these structures will be a necessary input in the future.

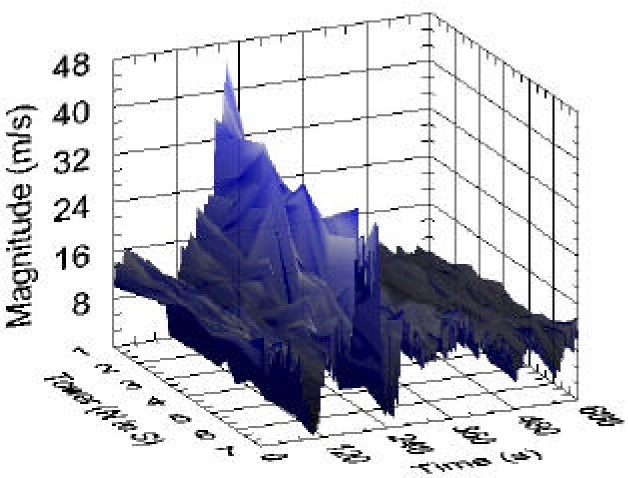

Figure 3. Space-time history of a downburst at 10 m height at Lubbock, Texas – June 4, 2002 (image provided by John Schroeder, Texas Tech University)

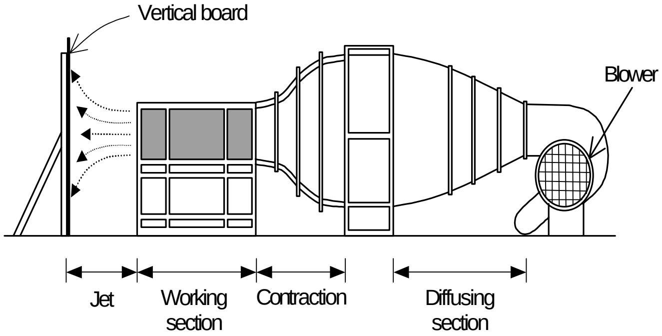

Figure 4. Pilot simulation of a thunderstorm downdraft – CSIRO Australia (1990-92)

3.2 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 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 as illustrated in Figure 5), 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

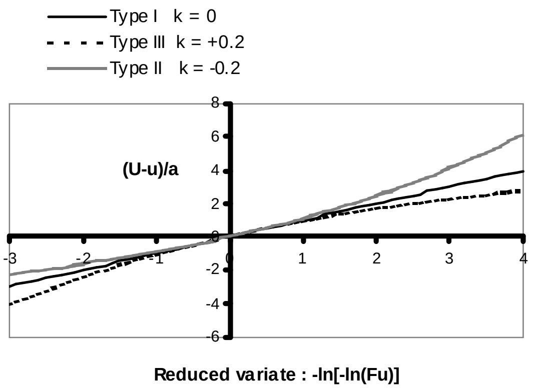

Figure 5. The Generalized Extreme Value Distribution, showing effect of shape factor, k

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 wind speed 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.

3.3 Climate change and the effect on design wind speed

The evidence of increasing ocean temperatures and water level rises in the atmosphere in the last hundred years is now providing evidence that climate change due to human activity is having an effect on the world's weather. For example, the worst drought in 100 years in Australia, and some of the worst bushfires in living memory in south-eastern Australia have just occurred, 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 seawater temperature of around 26^o 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. Atmospheric scientists and mathematicians with large-scale numerical atmospheric models will address some of these questions. 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.

Another significant source of extreme wind speeds 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 out 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. For example, the statement in the Commentary to the Australian/New Zealand Standard on Wind Actions 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 engineers will expect some guidance on this question.

3.4 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 windstorms, 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 tornados, the innovative work of Tachikawa in Japan on flat plates as missiles, [26], [27], and some recent interesting work in the U.K. by Wills *et al* [28], who defined the lift-off conditions for three generic debris types (Figure 6), 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

That wind-borne debris as an emerging area of study is indicated by the several papers n the topic at this Conference.

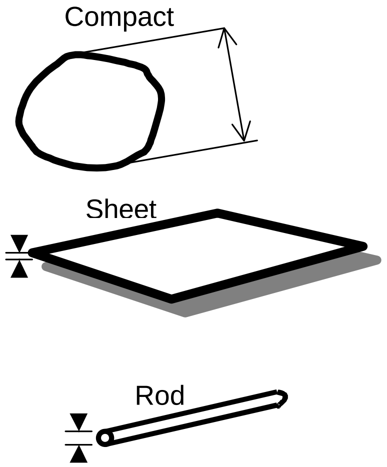

Figure 6. Generic debris types [27]

3.5 Database design

A long-term project in North America 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 code-writers and researchers will use the information.

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^o) 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. Figure 7 shows the 'total pressure fluctuations', represented by the sum of the eigenvalues in a P.O.D. analysis, for one of these building models. Plots such as Figure 7, that should show relatively smooth variation with wind direction, can be a useful indication of the data quality.

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. P.O.D. is a convenient way of reducing the vast amount of data generated in these tests to their essential components.

This project is organised and funded by the National Institute of Standards and Technology (NIST) in Washington, D.C.

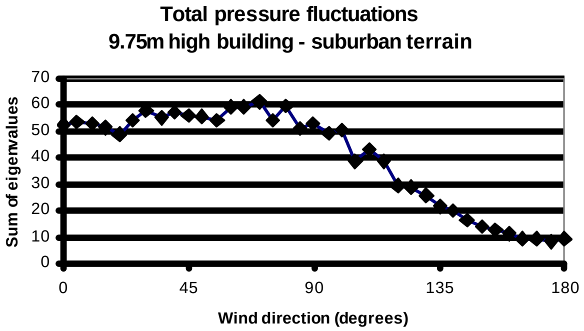

Figure 7. Measurements on a low-rise building model at University of Western Ontario for NIST

The ever-expanding Internet is an ideal repository for design data, and this has already been used to store high-frequency base balance data for generic high-rise buildings, by the group at Notre Dame University under Ahsan Kareem (www.nd.edu/~nathaz). Other data planned to be stored in this way includes time histories of wind speeds from hurricanes by Clemson University.

3.6 Wind economics

This Conference is also seeing the emergence of 'wind economics' as a sub discipline. As well as the insurance-related windstorm risk studies, which usually have dollars as the bottom line, we have papers on 'catastrophe bonds', post event employment changes and even the effect on the stock prices of insurance companies.

3.7 Fire-induced winds

Bob Meroney's paper on 'fire whirls' in this Conference may also indicate a new area of study. Although his work is directed primarily to building atria, there may well be applications in the natural environment. During recent severe 'bushfires' just outside the national capital of Canberra, Australia in late 2002, it was noted that the convection generated by the burning of pine plantations was sufficient to generate winds strong enough to damage the roofs of houses. Although some people were initially sceptical of this, Bob's paper indicates that this may well be a real phenomenon.

4 MORE OF THE SAME

4.1 Computational wind engineering – what is the future?

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 [29]. 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 at ICWE10 [30].

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.

4.2 Architect-driven building aerodynamics

Structural engineers and wind engineering will continue to be challenged by architects with exotic shapes for the roofs of sports stadia, and tall buildings (Figure 8). 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.

In other areas of building aerodynamics, there is scope to examine the effects of Reynolds Number on fluctuating and peak pressures. The fact that the peak roof corner pressures on a 1/10 scale model of the Texas Tech Building [31] fell almost exactly between the values reported from full scale, and from the 1/100 scale wind-tunnel models, was convincing evidence of a real effect. Complete explanations of the fluid mechanics of this phenomenon have not been given

There is room for further generic studies for buildings of non-rectangular planforms and elevations.

Figure 8. Tall building model tested in boundary layer wind tunnel, University of Western Ontario

4.3 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. The Messina Straits Bridge, the aerodynamics of which is discussed in several papers in this Conference, may exceed this. 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 aerodynamicists busy in the coming years, as is indicated by the number of papers on cable aerodynamics and vibration in this Conference.

4.4 The future for wind codes and standards

Wind loading codes and standards represent the major interface between structural and wind engineering. 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 driven by expansion in world trade and globalisation.

In Europe, the structural Eurocodes have had a lengthy and somewhat painful pregnancy, but the Eurocode 1 Part 1.4 Wind Actions is close to birth. The Australian and New Zealand Standards on Wind Loading are 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 (a working group meeting will be held following this Conference). The International Association for Wind Engineering organised two Workshops on International Codification for Wind Loads in 2000 and 2001, and some of the Working Groups set up to study various aspects of codification will report during this Conference. 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 that 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.

Meanwhile it is unfortunate (for the practitioner) that various national or international come up with their own versions of codified shape coefficients for a particular structural shape, often from the *same* database of wind-tunnel data. Although usually based on sound arguments, the resulting tables are often quite different from each other. Some bilateral cooperation at the working group level could improve this situation.

4.5 Wind energy

A major trend in the 21st Century will be the expansion of wind energy and this is being driven by the Kyoto Protocol on Greenhouse Gas Emissions.

Although the design of wind turbines is not a primary topic of this Conference, there are opportunities for participants 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. One of these criteria is fatigue, discussed in the following section.

4.6 Wind-induced fatigue

With the variety of extreme wind types of varying durations clearly being important for many locations, the duration of wind storms and the length of exposure to extreme winds needs more consideration. For example thunderstorm winds typically last only a few minutes (Figures 2 and 3), hurricanes and typhoons a few hours, and extra-tropical gales may last for several days. Duration of loading effects on materials is often expressed in the form of 'fatigue' criteria, including the cyclic fatigue of steel, and the 'static fatigue' of glass.

Failure of steel structures by wind-induced fatigue in synoptic wind events is a problem that clearly has occurred many times in practice (Figure 9). The designer rarely considers the problem at the design stage; this is largely because no workable design approaches have been available. The situation has improved recently with some simple closed form equations for along-wind fatigue damage rates and fatigue life now available [32]. These have been validated against direct calculation from full-scale measurements of fluctuating strain [33].

There is considerable potential for further work in producing 'designer-friendly' methods for dealing with wind-induced fatigue, initiated by both along-wind and cross-wind forces. These may be based on empirical fits to numerical solutions, and should consider more advanced models of material behaviour under repeated loading conditions.

Figure 9. Fatigue failure in a lighting pole [33]

4.7 Instrumentation

Finally I should say something about instrumentation for experimental wind engineering, as areas of investigation are often driven by the availability of the necessary equipment. I have already mentioned the application of automatic weather stations to full-scale measurement of infrequent windstorm events such as severe thunderstorm downdrafts. A technique of full-scale structural response measurement that is emerging is the use of Global Positioning Satellite (GPS) sensing equipment to monitor the movement of large structures such as bridges, towers and large buildings. This technique has already proved itself to be feasible in Japan, China and the U.S.

In the wind tunnel, dynamic multi-hole pressure probes, of the type shown in Figure 10, will probably replace hot-wire and hot-film anemometers for most flow measurement situations in wind engineering, including ground level measurements for pedestrian winds.

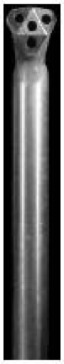

Figure 10. Dynamic multi-hole pressure probe ('cobra probe') (Picture provided by Turbulent Flow Instrumentation Pty. Ltd.)

5 CONCLUSIONS AND FINAL COMMENTS

After reviewing the state of the subject forty years ago, I have attempted to identify emerging issues for the next forty years. The importance or otherwise of issues is obviously subjective, and those selected for this paper represents only one person's viewpoint.

As a general comment, it is good to see that wind engineering is starting to re-focus on the needs of the practising structural engineer, and I congratulate the organisers of ICWE11 on re-introducing the practitioner stream at this Conference.

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

ACKNOWLEDGEMENTS

I am grateful to Professor Chris Letchford for providing an advanced list of papers for ICWE11, and the survey of 'burning questions' responded to by many experienced wind engineers, so I could, at least see what was already emerging in wind engineering in 2003.

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Recent Bridge Projects at Wind West Laboratory, Inc.

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www.westwindlaboratory.com

This begins the 25th year that the West Wind Laboratory, Inc. has been performing wind engineering studies. Nearly all types of studies have been performed, but the central focus remains, and always has been, evaluating the performance of long-span, flexible bridges in strong winds. Nearly 50 long-span bridge studies have been performed. All bridge studies were performed in association with Robert Scanlan and Nick Jones until Robert Scanlan's death, and with Nick Jones since. The West Wind Laboratory does all the experimental wind tunnel testing, and both teams perform independent analyses of the data - good for quality control. Following are descriptions of some of the more interesting, recent bridge studies that have been performed by the West Wind Laboratory:

San Francisco / Oakland Bay Bridge

New East Span
San Francisco / Oakland, California
T. Y. Lin International / Moffatt & Nichol Engineers, A Joint Venture, design engineers
CalTrans

This bridge is a very unusual, un-symmetric, 565 m span self anchored suspension bridge supported by a single tower near the middle of the span. The deck is a twin box section 71 m wide, with 8 lanes of traffic. Twin box bridges are extremely stable in extreme winds, but do have a tendency to b sensitive to vortex induced motions (the windward box drives the leeward box). Special mitigating vortex generators were designed to eliminate that vortex excitation.

New I-70 Crossing of the Mississippi River

St. Louis, Missouri to St. Clair County, Illinois
Modjeski and Masters, design engineers
(HNTB bypass project coordinator)
Illinois/Missouri DOT

When built, this will be the longest cable stayed bridge in the United States, by far. It will have a main span of 609.6 m. It too has a connected twin deck section with 8 lanes of traffic and a deck width of 67.7 m. It too is extremely stable in extreme winds, but also is sensitive to vortex induced motions (again the windward deck drives the leeward deck). Baffles and a maintenance platform in the gap were designed to eliminate the possibility of troublesome vortex induced motions. Not only were analyses performed for extreme atmospheric winds (generally perpendicular to the axis of the bridge), but analyses were also performed (time domain numerical simulations) to determine the multi-mode behavior of the bridge to tornadoes (200 mph peak wind speeds) that struck the bridge at 8 different locations along the bridge.

Lions Gate Bridge Reconstruction

(Construction Stage Wind Study)
Vancouver, British Columbia, Canada
Buckland and Taylor, design engineers
American Bridge / Surespan Contractors A Joint Venture, contractors
BCTFA

We performed the wind engineering studies for the construction phase of this project, for the contractors. This was an extremely unusual project because the bridge was literally rebuilt while open to traffic. From a wind engineering point of view it was particularly interesting because the critical flutter wind speed of the

existing bridge was lower than the required criterion during construction. The performance of the bridge in strong winds first had to be improved beyond the construction criterion so that, when the bridge was cut, the critical flutter wind speed never dropped below the criterion. That was achieved by adding covers to construction, pedestrian walkways. The covers acted as aerodynamic dampers that improved the performance of the existing bridge significantly. In all, nearly 100 buffeting and stability analyses were performed for various construction configurations, with and without dampers, with various linear and non-linear connectors, etc., etc., etc.

Carquinez Straits Bridge (3rd crossing)

San Francisco Bay
Deleuw-OPAC-Steinman, design engineers
CalTrans

This is one of the longest suspension bridges built in the United States in many years. It has a main span of 726 m, and has a streamlined box deck section. This was particularly interesting because, while very streamlined, the critical flutter wind speed was very sensitive to the solid ratio in the bicycle railing. Reducing the solid ratio of the bicycle railing from a typical 28% to 13% more than doubled the critical flutter wind speed (and was required to meet the design criterion).

Pearl Harbor Memorial Bridge

(I-95 at New Haven, Connecticut)
URS Corporation, design engineers
ConnDOT, FHWA

The bridge consists of a pair of bridges of the extradosed type. These are essentially long-span box girder bridges, reinforced with cables. The cables typically are few in number, and typically have shallow angles with the deck. Two complete designs, one with a concrete deck and one with a steel deck, were analyzed and taken to completion. The bridges, in their completed states, are very stable, but they do show some sensitivities during construction.

Earlier wind engineering studies have included the last, and certainly not the least, long-span suspension bridge in the San Francisco area, the Golden Gate Bridge. We performed the section model studies to refine and improve the aerodynamics of the deck cross-section. We proposed modifications (that were designed by T. Y. Lin International) that would increase the critical flutter wind speed from a low 60 mph to over 105 mph. Over 50 configurations were investigated. For that study RWDI performed the terrain model tests, and taut tube model tests. Those modifications are included in a seismic retrofit project that has not yet been implemented.

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