FULL-SCALE, WIND TUNNEL AND CFD WIND ENGINEERING STUDIES

A variety of methods can be used to obtain wind engineering design information. These include codes of practice, full-scale, wind tunnel or Computational Fluid Dynamics (CFD) studies. Each of these has their advantages and disadvantages, some of which are listed in the table below:

Table 1. Relative advantages and disadvantages of wind engineering techniques.

Method	**Advantages**	**Disadvantages**
Codes	• Easy to use. • Quick (A few hours or days) • Can be carried out by designers who do not have specialised wind engineering knowledge. • Inexpensive	• Only applicable to basic building shapes. • Can be too conservative.
Full-scale	• “The Real Thing”. • The only way to check validity of other techniques.	• Expensive • Slow (Many months or years) • Results can be site specific. • The wind has no “on” switch, you have to take what you get. • Building can not easily be turned to face the wind • The building has to be built before testing.
Wind tunnel	• Relatively quick (days - weeks) • Not too expensive for large developments. • New complex designs can be tested. • Effects of surrounding buildings can be incorporated. • Everything happens 60-100 times faster than in real life. • A wide variety of tests are available.	• The wind profile and turbulence must be modelled which is not always possible. • Results can be affected by Reynolds number mismatch. • Instrumentation needs to respond rapidly. • Difficult to measure everything. • Requires specialised knowledge.
CFD	• Variations on a design easily studied. • Data for all points in the flow is available. • Not too expensive.	• Requires expert knowledge. • Not always reliable. • Still requires significant computer resources. • Only mean flows are easily modelled.

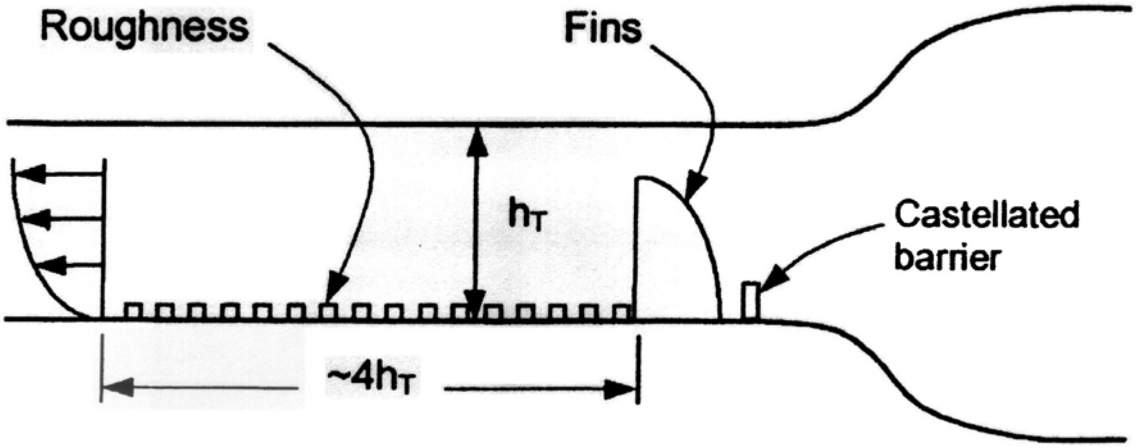
In the follow pages the breadth of wind engineering studies is illustrated by taking a look at the activities at three research and testing centres: The Silsoe Research Institute (UK) which specialises in full-scale studies and the Boundary Wind Tunnel Laboratory at the University of Western Ontario and The University of Auckland, New Zealand.

First, some background information concerning wind tunnel testing is given.

Wind tunnels for wind engineering investigations

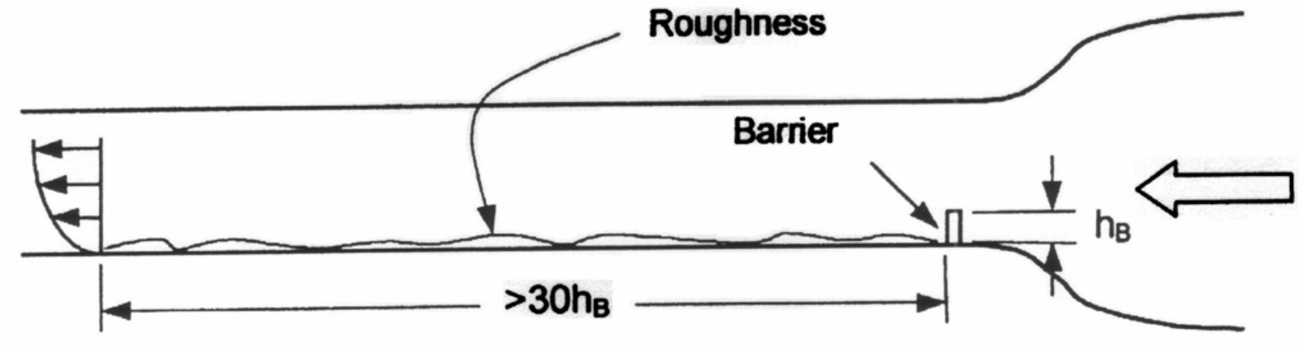
Modern wind tunnels for wind engineering studies are very different from those used for aerodynamic testing. In the latter case the objective is usually to achieve uniform flow with low turbulence intensities. For wind engineering purposes we need a large working section that is long enough to allow the development of a thick turbulent boundary layer along the ground. This allows simulation of the lower part of the atmospheric boundary layer, usually at scales up to 1:100.

Generation of a thick turbulent boundary layer (with the velocity profile shape, turbulence intensity levels and turbulent length scales appropriately scaled with those at full-scale) is based on experience and rules of thumb. For wind tunnels with a short working section it is necessary to introduce turbulence into the flow very quickly to encourage the rapid growth of the boundary layer. This is normally achieved by having a row of vorticity generators at the start of the working section (also known as “fins”, “spires”, “sharks teeth” or “Counihan teeth” depending on the shape). These produce large amounts of turbulence at large scales over the height of the developing boundary layer. A barrier acts to take out momentum near the ground, which also hastens the boundary layer growth, whilst a fetch of roughness elements creates the appropriate friction to achieve the required turbulence levels near the ground and the correctly scaled values for z_o and U_*. Generally, large roughness elements are used upstream and decreasingly smaller ones are installed in the downstream direction. This allows the larger turbulent scales to be generated first. A typical arrangement is shown below.

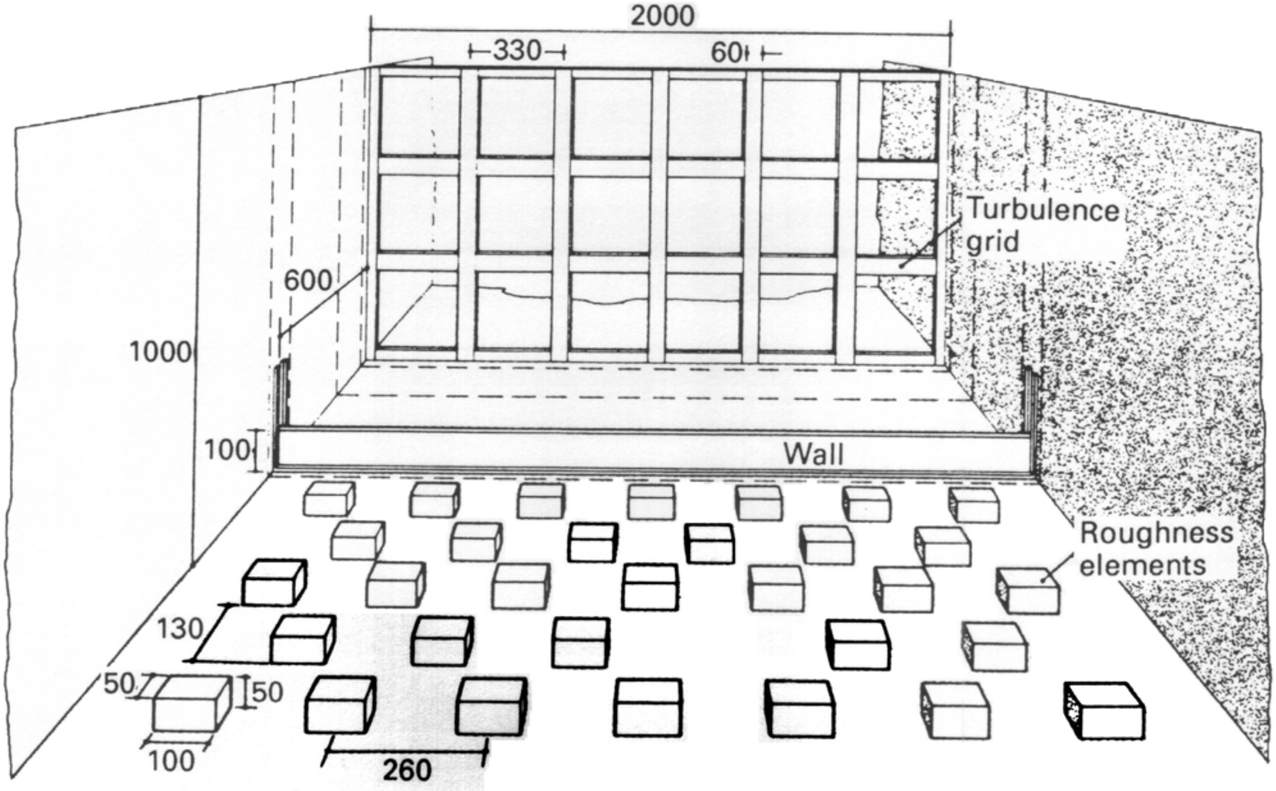


Method of generating a thick boundary layer simulation in a short test section

Rapidly forcing the growth of the boundary layer is the only way of achieving reasonably large scales in shorter tunnels but it also means that the quality of the simulation of the ABL is not as good. Ideally, where space allows, we prefer to use a longer test section (in excess of 20 m) to allow the boundary layer to grow more “naturally” over a fetch of roughness, as shown below.



Method of generating a thick boundary layer simulation in a long test section



Example of layout of barrier wall, roughness elements and a turbulence grid in a long working section wind tunnel (view looking upstream)

Example of a short test section, open return wind tunnel (fetch of approx 6m)
School of Engineering, University of Surrey, UK
(Note: the old Commodore PET microcomputer with 32k of memory!)

Wind tunnels may be open return, as shown in the photo above, where the air ejects into the laboratory (upwards at the near end in this case) or closed loop, where the air continually recirculates through the fan and around the system. The former design saves space but uses more power to move a given mass of air, whilst the latter case is more efficient but takes up considerable more space because of the return portion of the circuit.

Full-Scale studies at the Silsoe Research Institute, UK

The Silsoe Research Institute (SRI) has for many years been one of the leading centres in full-scale studies. With any form of modelling, such as wind tunnel or CFD, there is a need to benchmark results against full-scale data. Studies at SRI have included aspects such as:

The Silsoe Structures Building

This purpose built building has been used in a variety of studies relating to wind loads and wind flow around low-rise buildings. These include aspects such as:

- The external and internal pressures on the building and the relationships to the onset flow.
- Flow separation with both sharp and curved eaves.
- Pollutant dispersion in its wake.
- General flow patterns around buildings.
- Natural ventilation.

The Silsoe Structures Building

The Wall

The introduction of the new wind loading part of the UK building code, BS 6399, greatly increased the design loads for free standing walls. The data on which these requirements were based came primarily from wind tunnel studies. SRI was commissioned to carry out full-scale tests on a 2m high wall of variable length. The loads on one of the 2m x 2m panels could be measured both through load cells and pressure tappings. In the picture below the wind instrumentation can be seen in the foreground. This consists of a reference static pressure probe (pointing upwards), a directional pitot tube to measure the wind stagnation pressure (on the left) and a 3 component sonic anemometer which can quickly measure the wind speed in three orthogonal directions.

The wall with instrumentation and flow visualisation

Plastic Clad Greenhouses

SRI has carried out a number of studies of wind loads on these damage prone structures. Various designs have been tested at Silsoe, one of which collapsed under wind loads while the researchers were inside. Recent work has included a collaborative study where large models were tested in a French wind tunnel at CSTB (Nantes).

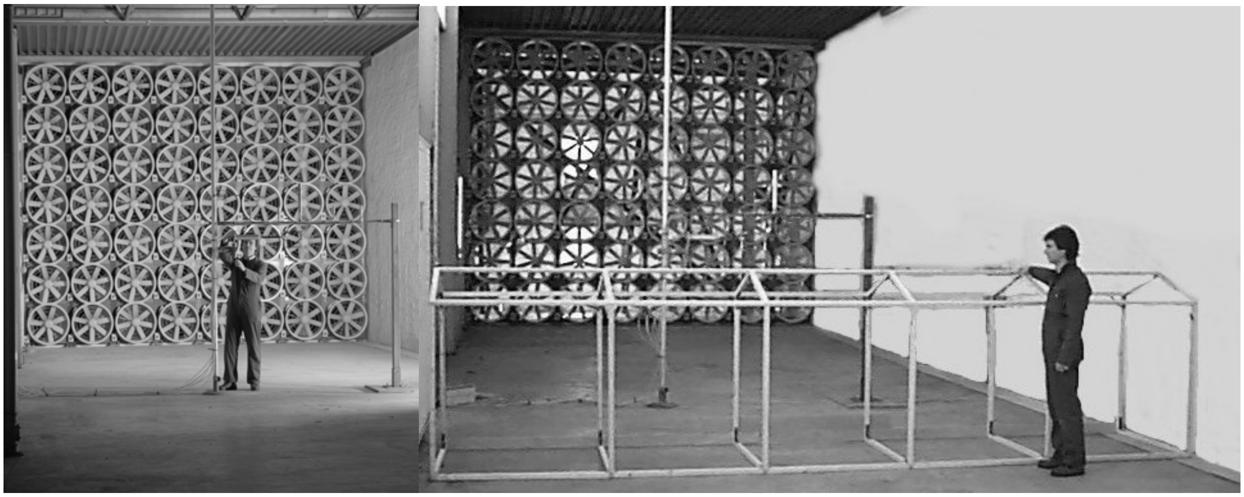
Wind tunnel testing (CSTB, Nantes) and use of plastic clad greenhouses

The Cube

This basic shape structure is being used for wind load and ventilation tests. The silver plates on the front face contain a tapping hole, which is connected through plastic tubes to a transducer. The cube sits on a turntable so that it can be turned to face any desired direction and can also be tilted in order to investigate the change in pressure coefficients with wind angle. The results from the cube have been used in an international competition for computational modelling.

The cube in its normal position and tilted

A laboratory for simulating atmospheric flow



The SRI Atmospheric Flow Laboratory

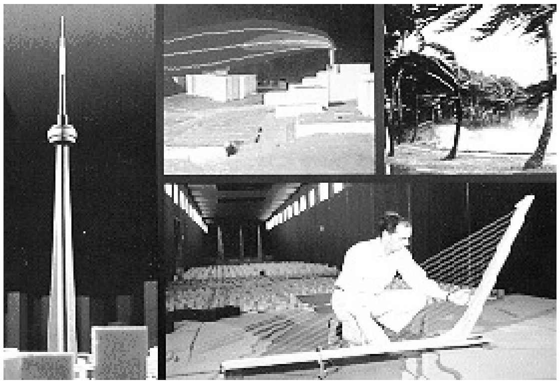
An atmospheric flow laboratory at SRI simulates conditions that occur in the lower part of the atmospheric boundary layer. The system operates using 56 variable speed fans supported on a 6m x 5m steel frame, with 28 individually addressable controllers each controlling 2 fans. The objective of the laboratory is to produce a flow that is similar in detail to the natural atmospheric boundary layer close to the planetary surface.

The facility, pictured above allows a number of different experiments to be conducted. These include study of the dispersion and deposition of pollutants and flow around and within buildings. It is also possible for the research group, led by Dr Roger Hoxey, to study wind effects on animals, birds and insects, as well as air movement within animal transport systems.

Wind tunnel studies at the University of Western Ontario, Canada

For many years the Boundary Layer Wind Tunnel Laboratory (BLWTL) at the University of Western Ontario (UWO) in Canada has been a leading centre for wind tunnel testing of wind engineering problems. The following includes material from their web site:

Studies of Wind Effects on Buildings at the Boundary Layer Wind Tunnel Laboratory



The methodologies for the study of wind effects on buildings are well established after the pioneering work of Prof. Alan G Davenport in the 1960s. With better understanding of the wind action and its interaction with the structure, modern designs have become more optimized, making accurate predictions of wind loads and effects a necessary step in the design process. Moreover, innovative designs both in building forms and structural systems have provided continuing challenges in the field of wind engineering. The following provides brief descriptions of the wind tunnel methods used in the studies of wind effects on buildings.

Overall Approach

The general overall approach in wind tunnel studies involves two major components. The wind climate statistics take into account the long-term variation of the wind speed and direction for durations longer than an hour. It is generally referred to in terms of the statistics of the hourly mean wind speed. Furthermore, this wind speed is generally defined at upper level where turbulence is low and where the, sometimes confusing, use of the peak wind speed is avoided. The upper level wind speed also avoids the local effect of topography and allows more consistent predictions within a geographical region. The analysis of the wind climate is carried out based on the statistics of the wind speed and direction, either obtained through long-term wind records or through numerical simulation of wind storms.

The second component is the aerodynamic data. These are obtained in wind tunnel tests. By reproducing the wind characteristics in the wind tunnel based on the reduced scale of the model, the scaled wind effects can be measured. Instrumentation used for the measurements of different quantities is described in more detail below.

The predictions of wind loads and effects are obtained through the combination of the wind climate and the aerodynamic data.

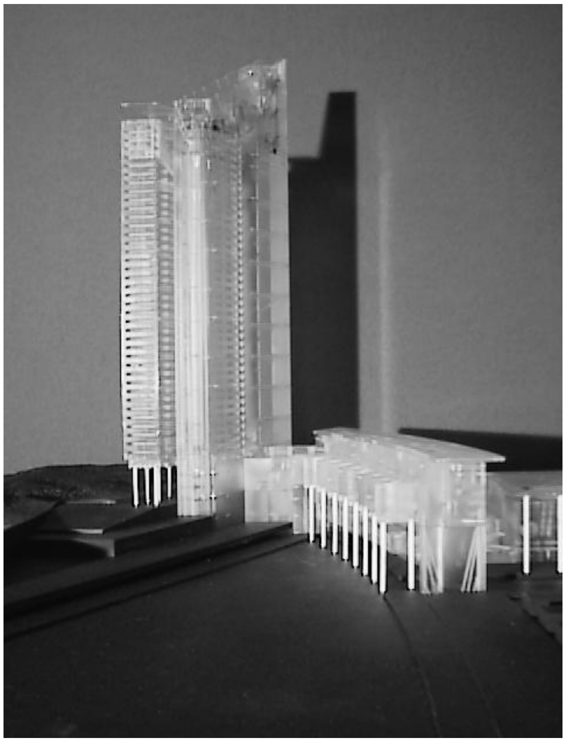
Wind Simulation

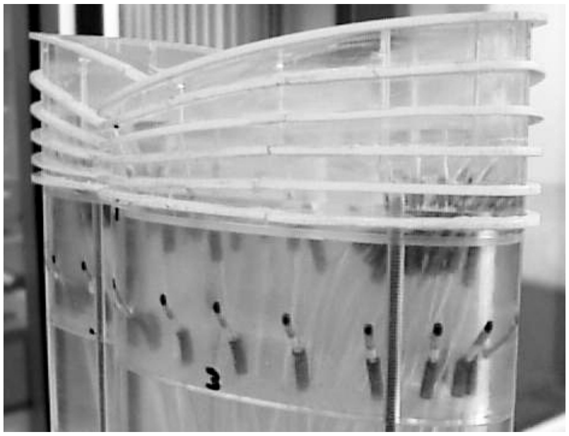
The testing of a reduced-size model in the wind tunnel requires the simulation of wind with the correct sizes of gusts and energy content at the range of scaled frequencies comparable to that of full scale. For testing of buildings, the simulation reproduces the planetary boundary layer in the lower 500 m or so of the atmosphere where the characteristics of the wind are significantly affected by the surface roughness such as topography, vegetation, buildings and other structures, etc. These wind characteristics are generally expressed in the form of a wind speed profile, a wind turbulence profile and a wind energy spectrum. Together these represent the correct variation of wind speed with height, of the gustiness of wind with height and the size of wind gusts in relation to the building or the building model.

Any combination of methods that can reproduce these parameters correctly at the test site are acceptable. However, by far the most effective way to reproduce the characteristics of boundary layer winds, is to use a long wind tunnel upstream fetch with appropriate floor roughness. This not only has the effect of producing the target parameters defined by homogeneous upstream terrain, it can also produce, through calibration of homogeneous terrains, simulation of mixed terrain commonly found in reality where the target characteristics are much harder to define.

Near the building site, the surrounding buildings and topography are modelled in detail so that the detailed variation of wind flow close to the building can occur naturally. Other devices such as spires, trips, barriers, vanes, jet flows, etc. can produce large variations of results and need to be used with caution.

Pressure Tests





A pressure test measures local pressures at discrete points on a wind tunnel or full-scale model, often made of acrylic. Each "pressure tap" on the rigid model is connected to a pressure transducer through PVC tubes. The point pressure measurements are interpolated or extrapolated to give pressure information on entire surfaces of the building.

The results are generally used to provide design data for windows, cladding, curtain walls, etc. Because of the use of this information for the design of relatively small structural components, which have relatively high natural frequencies, the measured peak pressures which include the mean and quasi-steady dynamic components can be used directly for design without consideration of the resonance of the structural components

The pressure measurements are carried out using a high speed pressure scanning system. Pressure scanners, each with 16 pressure transducers, can measure almost simultaneous pressure signals at a large number of tap locations. The current capability is about 1,000 locations. With the capability of the pressure measuring systems to handle large amount of simultaneous data points, discrete pressure point data can now be integrated to estimate the total loads on larger components as well as the whole building. The dynamic effects in these cases are considered, in full, using random vibration theory. There is now an established methodology in using the pressure data to determine overall structural loads and responses.

Force Balance Tests

A force balance test is the most effective method in determining the overall structural loads and responses. First developed at the Boundary Layer Wind Tunnel Laboratory in the early 1980s, it represents a simple, fast and cost effective alternative to aeroelastic model testing for most buildings. Using a light and rigid model made of a high-density, structural foam material, base shears and moments are measured. With most buildings having an inherent near-linear mode shape, the base moment can be used to effectively estimate the generalized forces on the building. The force balance model is used only to measure the mean and quasi-steady dynamic forces. The resonant dynamic component of the wind loads and responses are then calculated using the dynamic properties of the building supplied by the structural engineer and the aerodynamic properties of the building measured in the wind tunnel. Because most of the dynamic structural properties are introduced at the data analysis stage, the wind tunnel test data can be used effectively to carry out parametric studies on the variation of dynamic properties such as natural frequency, damping value and mass. Results from the force balance tests generally include the displacements of the building, the acceleration of the building at the top floors, the overall overturning moment of the building and an estimate of the equivalent static design load distribution over the height of the building.

The basic instrumentation used in a force balance is the base balance. In addition to the original high frequency base balance, which offers higher sensitivity, the Laboratory also routinely uses a more robust force balance.

Aeroelastic Model Tests

For buildings with unusual geometry, highly non-linear mode shapes, strong structural coupling and/or anticipated significant motion-induced forces, aeroelastic model tests are required.

- **Two degree-of-freedom stick model tests**
  A two degree-of-freedom "stick" model is a simplified aeroelastic model that has a rigid upper portion of the building. The modelling does allow overall building movement in order to take into account of motion-induced forces. The stiffnesses in the principal directions are introduced through spring sets at the bottom of the building. An eddy current damping device produces the required damping. Overall base moments, top displacements and accelerations are measured in the "stick" model tests. Torsional properties are generally not modelled.
- **Multi-degree-of-freedom aeroelastic tests**
  The behaviour of a multi-degree-of-freedom model effectively resembles that of the corresponding full-scale structure. The full aeroelastic model used in long span bridge testing is, in fact, an example of a multi-degree-of-freedom aeroelastic wind tunnel model. In the case of a tall building, the structure is generally lumped into manageable number of segments. The structural properties and the mass distribution are modelled in these lumped segments.

A lightweight shell is manufactured to provide the correct building geometry for the measurements of the aerodynamic forces. Designed properly, the model can reproduce all the properly scaled dynamic properties of the full-scale structure including the frequencies and mode shapes in all three principal directions. Although highly complex and costly to build and test, this is the most reliable method to obtain the response of buildings where motion-induced effects are significant.

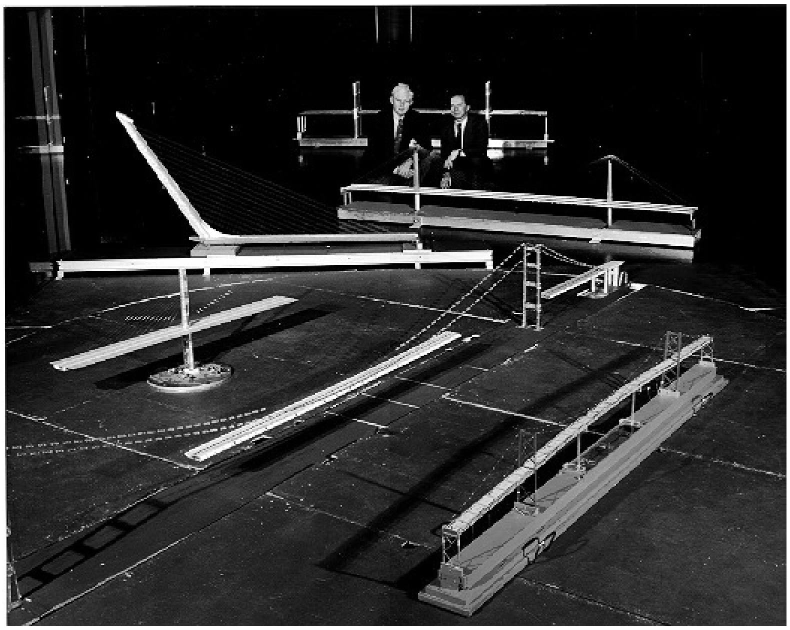
Pedestrian Level Wind Environment

The testing of the pedestrian level wind environment around a building is generally focused on the comfort and safety of pedestrians under strong wind condition. Measurements of wind speed condition are usually made at about 16 to 30 locations. These can be either carried out using hot-wire anemometry or using pressure probes. Both methods produce wind speed data so that decisions can be made regarding the appropriateness of planned activities; and in very strong wind condition, regarding the safety of the pedestrians and damage to property (such as furniture or plantation being carried off).

Prediction of Wind Speeds, Wind Loads and Responses

In all of the above, the resulting aerodynamic data are expressed in wind speeds, pressures, loads or responses for various wind directions. The local wind climate in the form of probability of wind speed and direction is then combined with these aerodynamic data to provide a probabilistic prediction of these quantities regardless of wind direction. Simply said, the 50-year return prediction represents the level of responses that will occur, on average, once in 50 years regardless of wind direction. This is accomplished by accumulating, over all wind directions, the probability of wind speed reaching the required level to produce such responses.

Outline Of The Approach To The Study Of Wind Action On Long Span Bridge



Prof. Alan Davenport and Mr. Peter King with some of the long span bridge full aeroelastic models tested at the Boundary Layer Wind Tunnel Laboratory.
(from top to bottom: The C&D Canal Bridge (steel alternate), Delaware, The Clark Bridge (concrete alternate), Illinois; Paso del Alamillo Bridge, Spain; The 6th Street Bridge (concrete alternate), West Virginia; The Tsing Ma Bridge, Hong Kong; The A. Murray MacKay Bridge, Halifax, Canada.

In the evolution of modern, lightweight, structurally innovative deck systems for long span bridges the definition of realistic wind loading is essential. This definition should include not only the identification of any aerodynamic instability but also its loading under turbulent flow conditions representative of full scale. Recognition of the importance of lift and torsional loading in addition to drag has changed the perspective on the definition of design loads. The evaluation of the wind action on a major bridge includes some or all of the following aspects:-

Selection of Bridge Deck System: There is now a reasonably broad range of bridge cross-sections that have been tested, from which guidance can be obtained on favourable aerodynamic characteristics. A review of this material with the designers should assist in the development of a preferred configuration. This review should be carried out in parallel with a dynamic analysis of the bridge frequencies and mode shapes.

Measurement and Definition of Aerodynamic Characteristics: The bridge cross-section selected should be tested using an elastically mounted section model and/or a "taut strip" model. These models are studied in turbulent and smooth flow to determine their aerodynamic response characteristics and any tendency to instability. Critical wind speeds for instability are established. If stability characteristics are not satisfactory, modifications to the aerodynamic cross-section can be made. Determination of the response under service wind speeds, together with the study of climate, permits the assessment of aerodynamic loads.

Study of Wind Climate: The definition of wind climate is a vital link in the definition of loading. This is done usually through a detailed study of meteorological records for the region in which the bridge is situated. Special consideration is given to the influence of topography and the effect of wind direction on the risk. An important feature of the wind climate in coastal areas may be the occurrence of hurricanes. To study the incidence of hurricane winds at bridge sites a hurricane simulation investigation can be used which was developed precisely for this purpose. Based on the historical data for this region, on hurricane tracks, their proximity and direction, central pressure, radius to maximum winds, and forward speed, a Monte Carlo simulation is used to generate a statistical population of hurricanes representative to the region and at representative distances from the bridge. Knowing the aerodynamic response, the response of the bridge to each of these storms can be "monitored in the computation and extremes can be recorded. In addition, the compatibility of these wind predictions with anemometer recordings in the area of large-scale extra tropical storms is examined.

The Prediction of the Bridge Response to Wind: Phases 1 and 2 of this description have been concerned primarily with the aerodynamic characteristics of the bridge cross-section and particularly its stability. Phase 3 has been concerned with the prediction of the wind climate at the bridge site. This, the fourth phase, is concerned with synthesis of this information and the prediction of the response of the selected bridge to these winds. This amounts to assessing the effective loads, both static and dynamic, which must be sustained by the bridge for different recurrence intervals (return periods). Final confirmation of the bridge behaviour can be undertaken on a dynamic (aeroelastic) model of the full bridge, tested for a representative range of wind speeds and directions and monitored for key responses (mid-span and quarter point moments, defections, cable tensions, for example). This study would be recommended in cases of innovative design and bridges of exceptional size and importance or unusual siting.

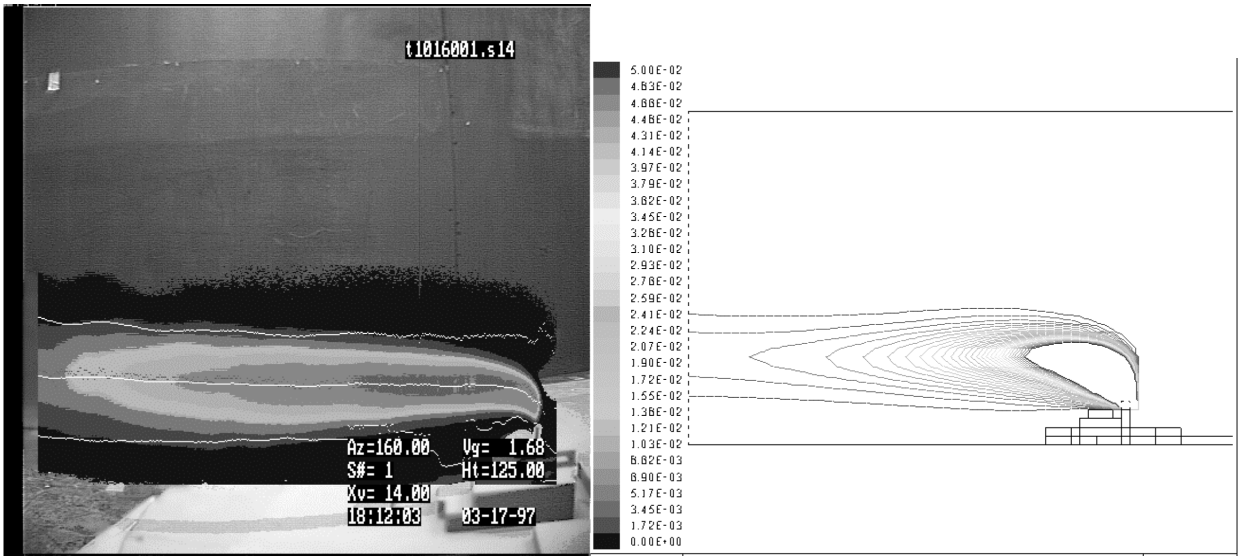
Special Aspects Construction stages: Special wind loading questions may arise during the construction. These concern the response of towers, especially during a free standing stage and the response of the deck structure when cantilevered out from the tower.

Cable response: The special questions related to cable oscillation through interference buffeting, vortex shedding or deck vibration may require investigation.

Damping enhancements: The critical role of damping in inhibiting wind induced oscillations makes the question of adding damping a serious question.

Fatigue: Special questions of the fatigue of elements of the deck and cables are deserving of recognition. Estimation of fatigue loading can be undertaken as a special aspect of the loading definition.

Pollution dispersion



Stack release : 1) Experimental Flow Visualization 2) CFD Concentration Contours
"Experiment versus CFD simulation for a dispersion study", H. Hangan, Proceedings of the Fifth Annual Conference of the CFD Society of Canada, Victoria, (1997) pg. 6-43

Wind Tunnel Experiments

Experimental pollution-dispersion studies are carried out at the Boundary Layer Wind Tunnel Laboratory. A typical study is built up in two phases:

<u>1) Plume geometry study:</u> This is a semi-qualitative analysis based on flow visualizations. The plumes (releases) are made visible by adding titanium tetrachloride to the gas mixture emitted from the release points. The wind tunnel model and the proximity area are illuminated with a narrow laser beam in both vertical and horizontal slices. A frame grabber and a digital image processing system are employed to record and analyze individual frames.

<u>2) Concentration measurements:</u> A source gas (usually a combination of ethane and nitrogen) is used as tracer and the correlated concentrations are sampled at particular locations by aspiring a continuous sample through a Flame Ionization Detector (FID).

CFD Simulations

An interesting option is to extend the concentration measurements to the entire flow field making use of Computational Fluid Dynamics (CFD) simulations. In order to ensure the reliability of this type of study the CFD simulations are first "calibrated" using the experimental measurements previously described (for a restricted number of locations). This CFD extension of a typical atmospheric dispersion study presents some important advantages:

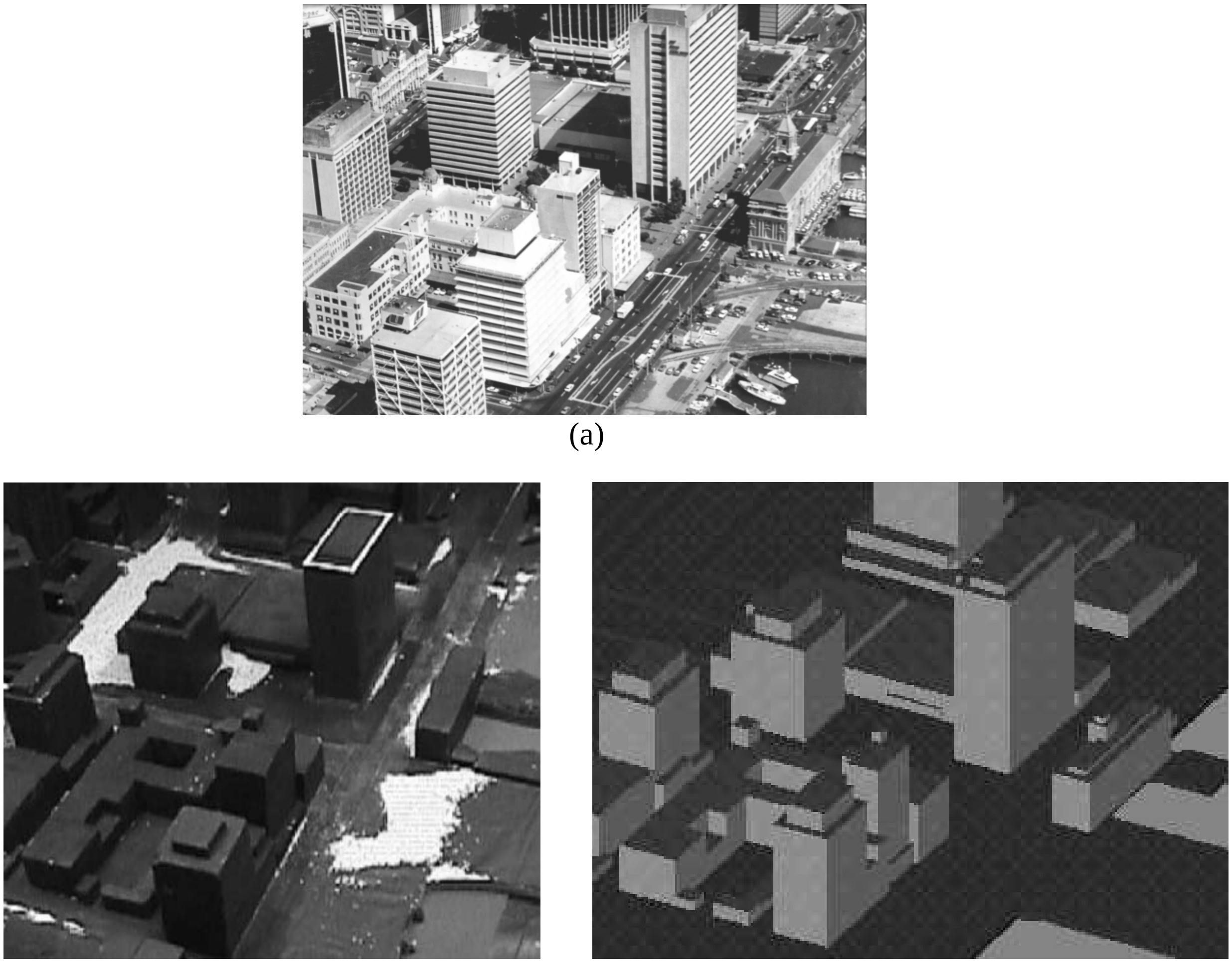
1) Extension of the concentration measurements for the general flow field
2) Identification of high concentration locations mainly for "complicated" releases, i.e. releases in built-up and topographic areas, close-to-ground horizontal releases, etc.
3) Easy change of release parameters for various case studies
This approach is part of a general concept that makes use of both in order to extend the area of expertise at the BLWTL.

Wind tunnel and CFD studies at the University of Auckland, New Zealand

The University of Auckland is not a major centre for wind engineering in the same way that SRI and UWO are, but is one of two active wind engineering centres in NZ. It has a boundary layer wind tunnel and a specialized sail testing tunnel and the laboratory is active in computational modelling of wind flows. Their work includes the following studies:

Pedestrian level wind studies

Auckland City Council requires that tall buildings, constructed in the centre of town, be tested to show that they will not have an excessive adverse effect on the wind environment. The technique that is used is to cover the streets with bran flakes and then to slowly increase the tunnel speed. At each stage a computer image is captured to see where the bran has been eroded. In this way the windiest areas are shown up by erosion at low tunnel speeds. In the figures below the bran can be seen in Figure 1b) and the composite picture generated by computer at the end of a run in Figure 2a). Similar images are created for 8 wind directions and then combined with wind statistics to estimate the probability that various wind speeds are exceeded. The District Plan lays down the frequency that these speeds can be exceeded depending on the intended use of the area. The requirements say that places where people sit around must be far less windy than road carriageways.

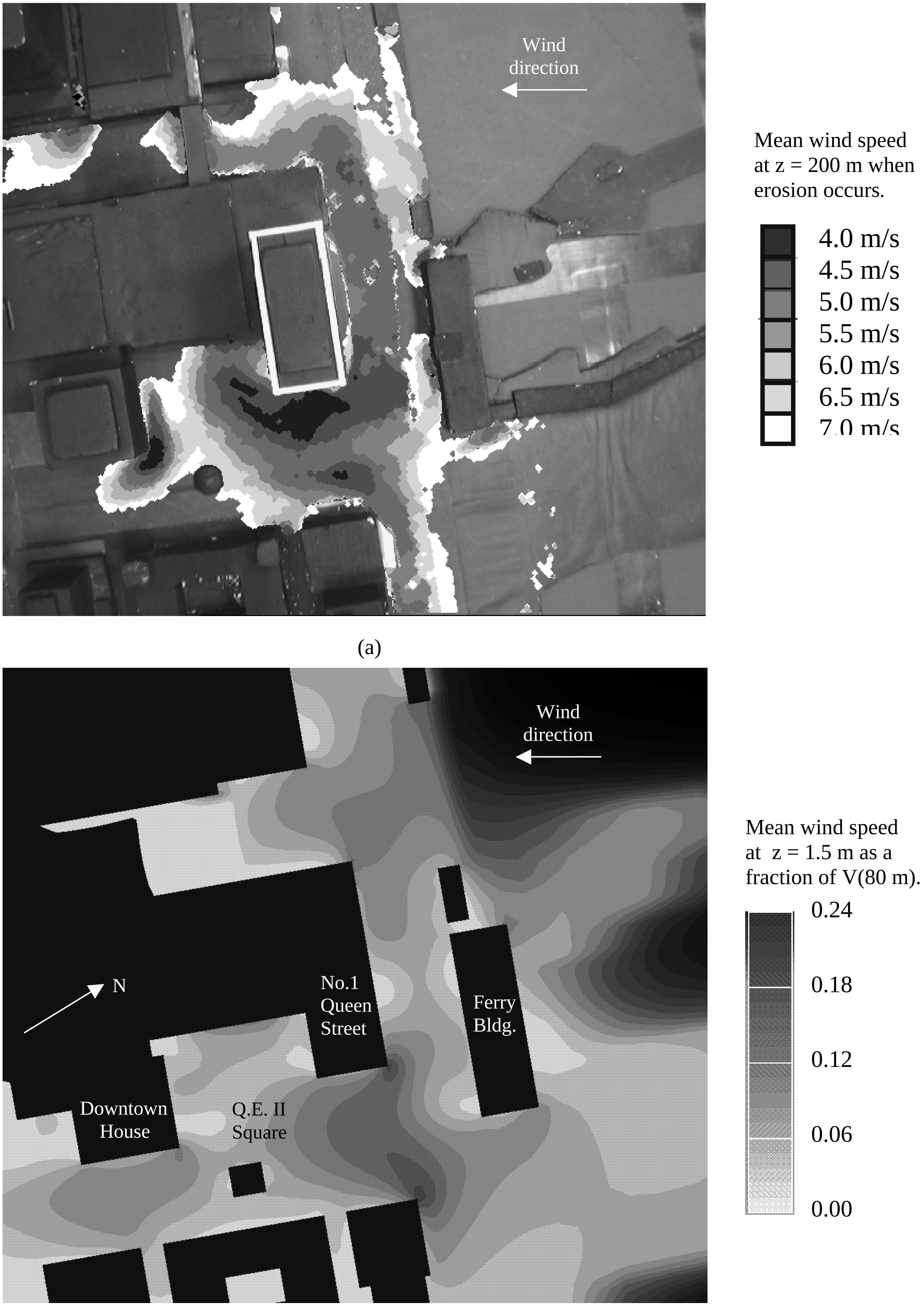


(a)

(b) (c)

Figure 1. (a) View of downtown Auckland from the North-East direction,

(b) corresponding wind tunnel and (c) computer models



(a)

(b)

Figure 2. Pedestrian level winds for wind direction 30° as determined from (a) erosion patterns in the wind tunnel and (b) computational fluid dynamic modelling

Computational Wind Engineering

Also shown above is the corresponding computational model (Figure 1c) and the resulting pedestrian level wind speeds (Figure 2b). The solution method used here is finite volume analysis. With this technique the solution domain is split up into lots of rectangular blocks (cells) as shown below. Some of these are blocked so that they form the buildings, as seen in Figure 1(c). Smaller blocks are used in regions where the flow is more complex.

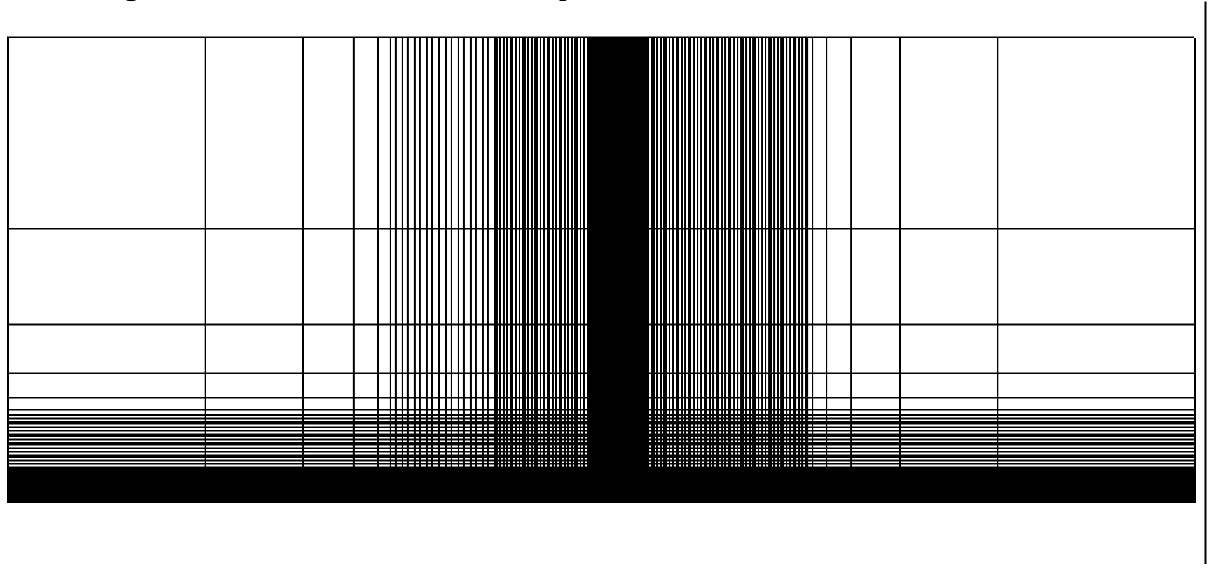


Figure 3. A finite volume mesh (the dark bands contain many small cells)

The computer program then creates millions of simultaneous equations which it solves itteratively. These equations are derived by applying the laws of conservation of mass, momentum, energy and other conserved properties to each cell. In the above model there are six equations for each cell, which are the conservation of mass, momentum in three directions, turbulent kinetic energy (TKE) and the rate of dissipation of TKE. The problem has about a million cells. From the results it is possible to extract velocity vectors as shown in Figure 4

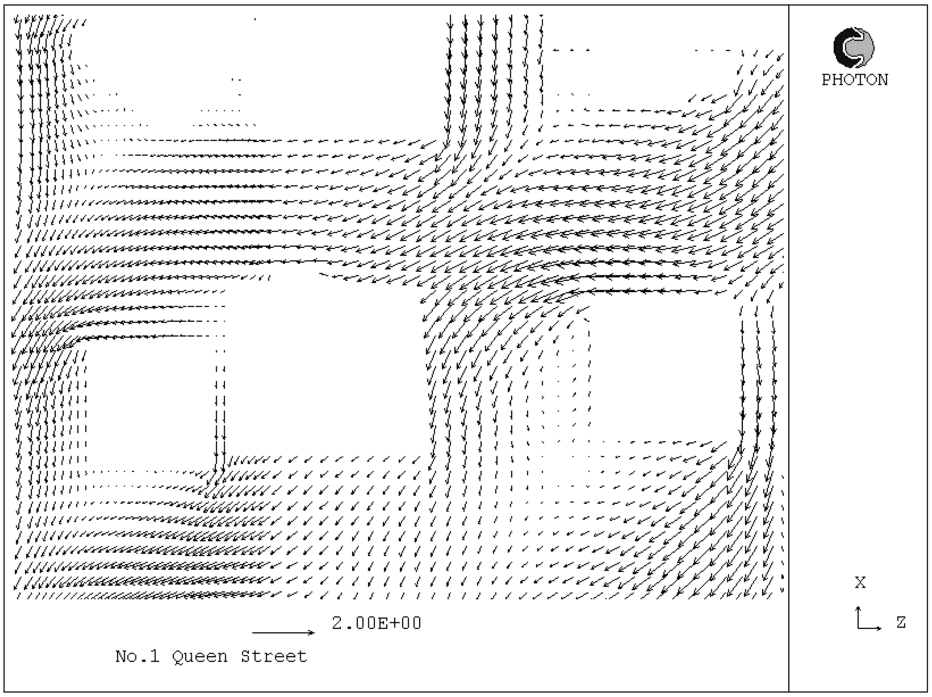


Figure 4. Velocity Vectors

It is also possible to plot contour maps of properties such as pressure.

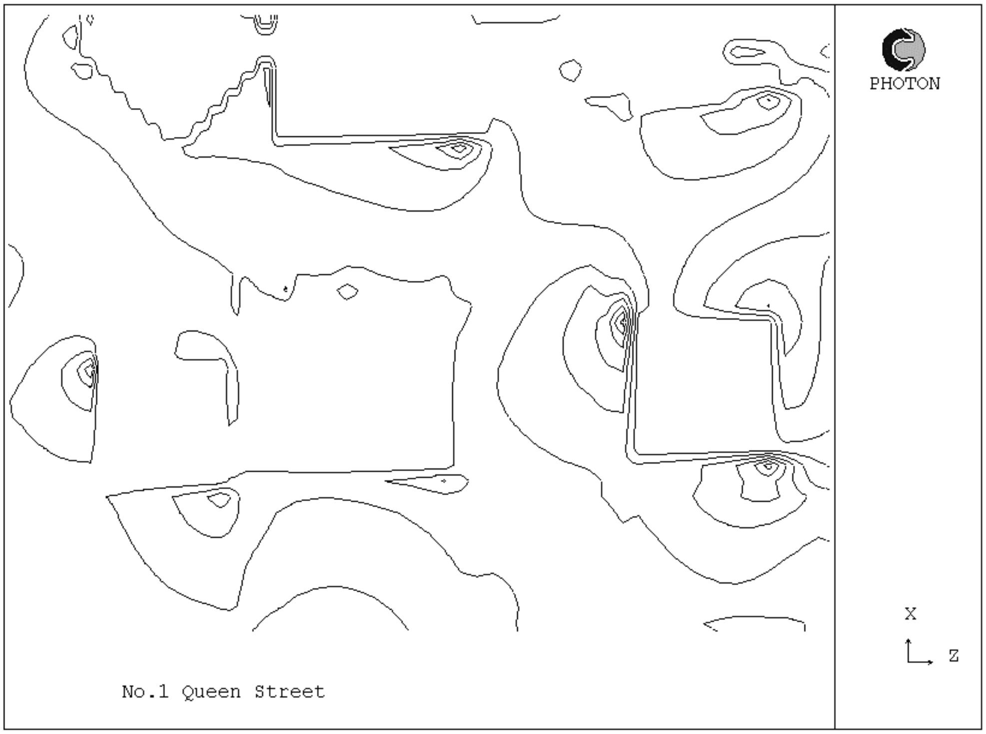


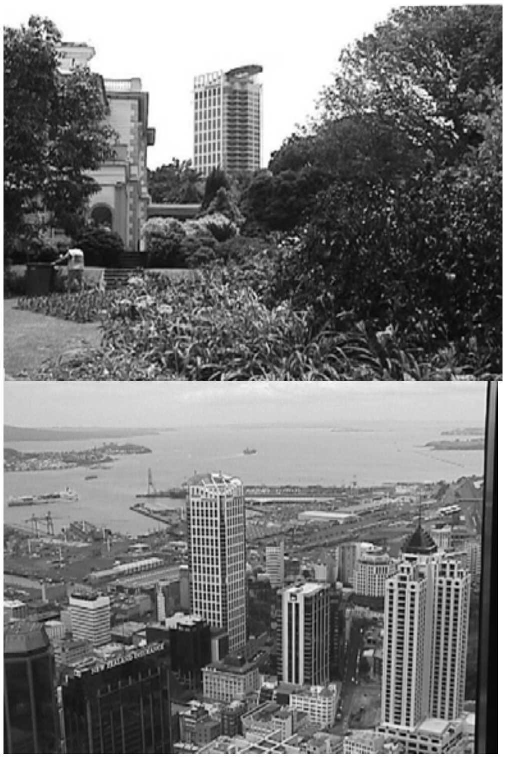
Figure 5. Pressure contours

Tall building design studies

In the design phase of tall buildings such as the Royal Sun Alliance Centre shown below, the University may get involved in a wide range of studies. For this building they were involved with

i) Pedestrian level wind environment
ii) Cladding wind pressures
iii) Special load estimates for the Halo.
iv) Dynamic response of the building (2 DoF model)
v) Mast dynamic response
vi) Sculpture dynamic response.

Figure 6. The RSA Building



For the cladding loads and Halo study the model was pressure tapped at 225 locations and these were sampled at 500 Hz for about 1 minute which is equivalent to about an hour in full-scale. The tubing system connecting the tappings to the transducers contained restrictors that were designed so that the system has a unity response up to about 200 Hz.

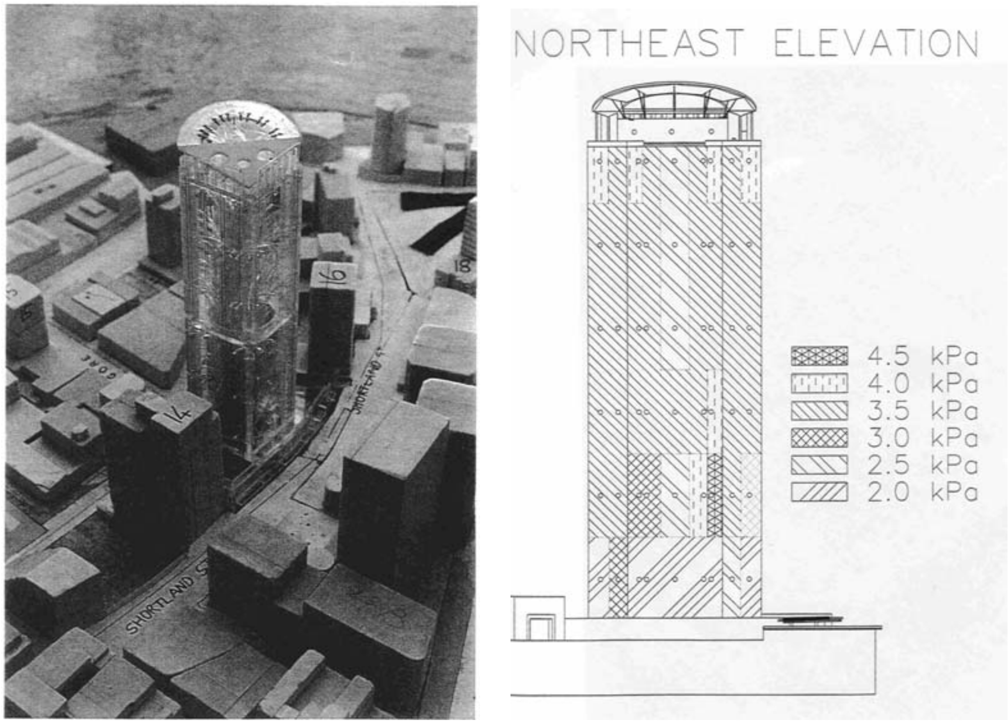


Figure 7. Wind tunnel model of the Royal Sun Alliance Building and the resulting design wind pressures

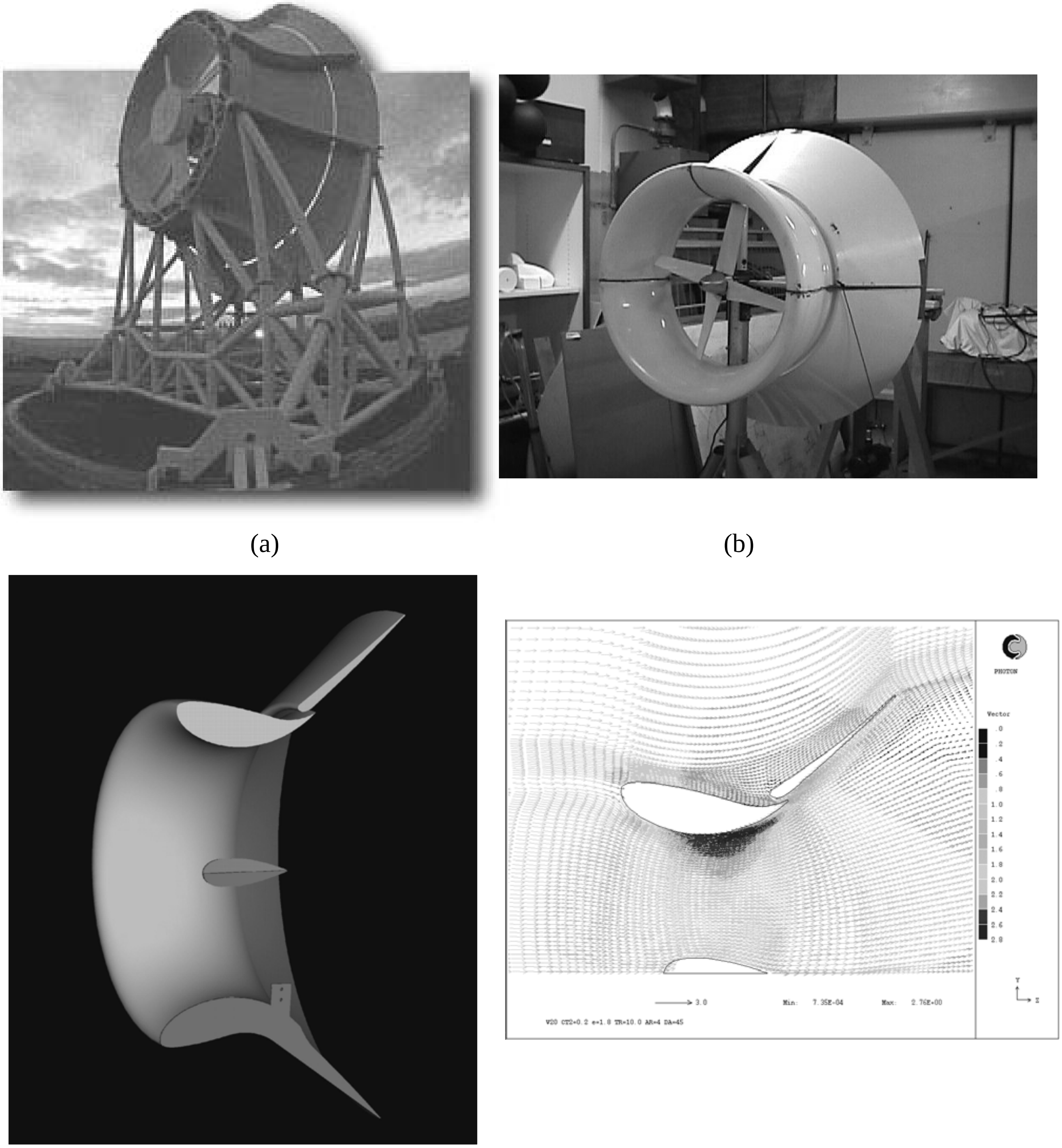
Yacht Research

In addition to the wind engineering work the group also has a specialized tunnel that is used for sail design. This tunnel twists the flow in order to simulate the combined action of the moving wind and moving yacht.

Figure 8. Downwind sail testing in the Twisted Flow Wind Tunnel.

Wind Turbine Design

The group are also involved with an Auckland company in the development of Diffuser Augmented Wind Turbines. This work has included full-scale, wind tunnel and CFD studies.



(a) (b)

(c) (d)

Figure 9. (a)   Full-scale testing of a DAWT, The VORTEC 7. (b) Wind-tunnel. (c) CAD and (d) CFD models of a later design.

Dr Eric Savory acknowledges the contribution of Prof Peter Richards (Uniersityv of Aukland, New Zealand) in providing information for this set of notes