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# QUALITY ASSURANCE MANUAL: WIND ENGINEERING STUDIES OF BUILDINGS

AWES

**AUSTRALASIAN WIND ENGINEERING SOCIETY, 2019**

**ACKNOWLEDGEMENTS**

The first AWES Quality Assurance Manual for Cladding and Environmental Wind Studies was published in 1994, with a second edition published in 2001. This third edition is largely a revision of the 2nd edition, benefiting from comments from many within the wind engineering community. Current revisions were made by a sub-committee comprising *A.W.Rofail, G.S. Wood* and *M. Eaddy* and approved by the AWES Committee. Contributors to previous versions of the manual have included (in alphabetical order), *P. Carpenter, R. Denoon, J.C.K. Cheung, J.D. Holmes, K.C.S. Kwok, C.W. Letchford*.

## PREFACE

This Quality Assurance Manual is intended to provide guidance to the practising construction industry professional on the conduct of wind tunnel testing and alternative studies for buildings and structures. This Manual should assist users in specifying wind tunnel testing appropriately and ensuring that basic testing requirements are met. Guidance is given regarding the applicability of alternative techniques such as Computational Fluid Dynamics (CFD).

The opening italicised paragraphs of each section are *minimum normative* requirements for wind tunnel testing. The subsequent paragraphs provide *informative* commentary to allow the user to understand the basis of the requirements and assess whether the minimum requirements are sufficient for a particular project.

## SCOPE

This Quality Assurance Manual sets out minimum requirements for the wind tunnel testing of buildings and structures in simulated boundary layers. Although primarily intended for use in Australasia, the requirements and commentaries are internationally applicable.

The Manual does not cover very specialised testing techniques (e.g. long-span bridge test techniques), but the general principles in Section A still apply in these cases. Neither does the manual cover testing in thermally stratified, non-fully developed boundary layers, or highly transient flows.

## PART A. GENERAL

**A1. Methodology**. *Design information should be provided for whatever wind type is appropriate for the site in question, i.e. gales, tropical cyclones, and thunderstorm downdrafts/outflows (tornadoes are excluded).*

The use of a boundary-layer wind tunnel with acceptable methods of simulation (see Section A2), is currently regarded as the only acceptable method for generating design information, irrespective of wind type (i.e. gales, tropical cyclones or thunderstorm downdrafts/outflows). Computational fluid dynamics techniques are not yet capable of providing acceptable calculations of the fluctuating and peak pressures on a structure, although they may be used to investigate **mean** environmental wind speeds depending on the turbulence scheme and transient nature of the model used (Section C1).

A general reference for boundary-layer wind tunnel techniques is Reinhold (ed.) (1982). Information on wind tunnels and modelling techniques is also given in the textbooks by Aynsley, Melbourne and Vickery (1977), Holmes (2015), and papers like Cermak (1975). In addition, the American Society of Civil Engineers (1999, ASCE 49-12, ASCE 7-16), and the Council on Tall Buildings and Urban Habitat (2013) have published guides to wind tunnel testing techniques for buildings and structures.

**A2. Boundary-layer Simulation.** *The boundary-layer occurring during strong winds produced by the wind storms characteristic of the extreme winds at the site in question should be adequately simulated in the wind tunnel.*

Wind-tunnel simulation of stationary atmospheric boundary layers requires the basic characteristics of the natural wind to be modelled at reduced scale. The natural wind at a site possesses the characteristics of the approach flow modified by adjacent natural (topographical) and man-made features, giving rise to a “near-field” flow.

Apart from atmospheric dispersion studies, strong wind events will govern engineering design through strength and serviceability (human comfort) criteria. Under these circumstances thermal stratification effects, with the possible exception of thunderstorms, will be insignificant and the approach flow may be considered neutrally stable. For thunderstorm downburst winds, which have highly-transient characteristics, an acceptable wind structure is still being developed and hence these flows are modelled with the same characteristics as gales or tropical cyclones for the present.

These types of flows are usually modelled in boundary layer wind tunnels (BLWT) which have the common characteristics of large cross sections (2 m or more in width and height) and long lengths (10 m to 30 m) for flow development.

**A3. Approach Flow.** T*he minimum requirements for an acceptable simulation of a neutrally stable atmospheric boundary layer are the modelling of:*

*(a) the variation of mean wind speed with height,*

*(b) the variation of longitudinal component of turbulence with height,*

*(c) the integral scale of turbulence, and*

*(d) a zero longitudinal pressure gradient.*

*The mean speed and turbulence intensity in the approach flow shall be modelled to within 10% of their target values. The integral scale shall be within a factor of 3 of the value determined from the chosen geometric scaling ratio (Section A5).*

Suitable models of the atmospheric boundary layer for evaluation of the wind tunnel simulation are those due to Deaves and Harris (1978), which is incorporated in the Australia/New Zealand Wind Loading Standard (Standards Australia, 2011), ISO 4354 (2009), and Engineering Science Data Unit (1985 and 1986). These models use a logarithmic law to describe the mean wind speed profile with the roughness length, $z_0$, being the main parameter.

The specific requirements (a-d) can be satisfied by reproducing the full depth of the atmospheric boundary layer, but this will usually result in a small geometric scale. For medium to low buildings, partial depth simulations to a height of 100 m are sufficient, although constant shear stress requirements should be observed (Cermak and Cochran, 1992).

Standard techniques, for producing mean wind speed profiles and turbulence characteristics in both full and partial depth simulations include the use of spires, fences, grids and surface roughness elements as described by Reinhold (1982), Melbourne (1977a), Cook (1978), Holmes and Osonphasop (1983), Barlow *et al.* (1999), and Cermak and Cochran (1992).

The approach flow is usually modelled as an equilibrium boundary layer. Thus the characteristics of the approach flow should be that of the terrain extending upwind of the periphery of the near field model (Section A4) a distance of at least 60 times the reference height of the study building taking into account terrain category changes. The zero longitudinal pressure gradient is usually achieved through use of features such as adjustable ceilings, divergent walls, or slotted or vented wind tunnel boundaries. An alternative to this requirement is the application of blockage corrections (Section A7).

**A4. Near-field Flow.** *Adjacent physical features such as significant buildings, structures or topography, will influence the near field flow and must be included as part of the local wind flow simulation. In general, all major structures and topographical features within a radius of at least 300 m from the building site should be modelled to the correct scale, to an accuracy of 10% or better.*

The extent to which upwind buildings should be included in the modelling depends on whether the site is immersed in a city centre, or is a new high-rise development in which the surroundings are generally low-rise, but with a few isolated high-rise buildings upwind for some directions.

The accuracy of model detail can be reduced with distance from the site. Section A9 describes the accuracy requirements for the building model under test, and for the surrounding buildings. New buildings under construction, approved, or planned within the next five years should be considered, and may require testing of the subject structure in more than one surrounds configuration.

**A5. Geometric scaling ratio (wind model).** *The geometric scaling ratio of the atmospheric boundary layer model shall be determined from ratios of the roughness lengths ($z_0$) and integral scales of longitudinal turbulence ($L_u$). i.e.:*

$$L = \frac{(z_o)_m}{(z_o)_p} = \frac{(L_u)_m}{(L_u)_p}$$

*where the subscripts indicate: m for model and p for prototype.*

*This length scale sets the geometric scale of building models to be used in the wind tunnel.*

In practice it is possible to have a distorted integral scale of turbulence ratio, up to a factor of 2 or 3, (see Section A3), without significantly affecting measurements, Surry (1982).

**A6. Velocity scale.** *The wind tunnel reference mean velocity shall be chosen to maximise the sensitivity of the measurement instrumentation (e.g. pressure transducers, force balances, and anemometers). The velocity scale for the simulation is given by:*

$$\bar{V} = \frac{\left(\bar{V}_{ref}\right)_m}{\left(\bar{V}_{ref}\right)_p}$$

*where the prototype full-scale mean velocity $\left(\bar{V}_{ref}\right)_p$ is the design **mean** wind speed at the reference height at the site in question and taken at the wind speed relevant to the design.*

The velocity scale in conjunction with the geometric length scale will determine the time (*T*) and frequency scales (*N*).

$$T = \frac{L}{\bar{V}} = \frac{t_m}{t_p} \qquad \text{and} \qquad N = \frac{1}{T} = \frac{n_m}{n_p}$$

These scales are necessary to determine wind tunnel instrumentation sampling and frequency response requirements.

**A7. Blockage ratio.** *The blockage ratio, defined as the projected area of the near field simulation and the wind tunnel cross sectional area, should be less than 10% to minimise the requirements for blockage correction. In addition, the building model under study should not exceed half the wind tunnel height, or be located outside the middle half of the turntable.*

The constraining effect of wind tunnel walls leads to flow patterns not truly representative of full scale. Blockage corrections to overall mean forces can be applied as outlined in Reinhold (1982). It is still unclear as to how blockage corrections should be applied to local fluctuating pressures in highly turbulent boundary layer flow and thus it is recommended to minimise blockage or adopt tolerant wind tunnel techniques as described in Section A3 to avoid longitudinal pressure gradients. Blockage ratios higher than those recommended above may be used where blockage tolerant techniques are adopted. The constraining effects of the side walls of the wind tunnel can be minimised by locating the test model as centrally as possible on the wind tunnel turntable.

**A8. Minimum Reynolds Number.** *Tests shall be carried out at a Reynolds Number based on the minimum building width and on the mean wind speed at the top of the model, of* $5 \times 10^4$*, or greater. In the cases where there is extensive shielding, the minimum Reynolds Number should be achieved on the subject building without the shielding buildings present.*

Flows around bluff bodies such as buildings with sharp corners, are generally insensitive to Reynolds Number, above a minimum value. Below this minimum value, turbulence in the free-stream flow, and that generated by the building itself will be deficient in high frequencies, with consequent effects on the pressure fluctuations and peaks. For buildings with circular cross-sections, or with corners with large radii, the points of separation may be dependent on Reynolds Number. This is particularly the case for smooth, uniform circular cross sections, for which the Reynolds Number should be greater than $8 \times 10^5$ (Cheung and Melbourne, 1983; Macdonald *et al*., 1988, Eaddy 2004). Where buildings have radiused corners, or where curved surfaces have considerable roughness, (e.g. exposed perimeter columns, exoskeletons, deep balconies or large sunshades) some relaxation of these requirements may be possible, but reference to previous research (e.g. Basu, 1983) should be sought. The use of roughness to simulate super-critical conditions for mean drag forces is possible using the roughness Reynolds Number scaling method (Szechenyi, 1975; Holmes and Burton 2016). However, this technique has not been proven to accurately simulate cross-wind response (Eaddy, 2004).

Some distortion of the model may be required to satisfy Reynolds Number modelling requirements. For example, balustrades for repetitive floors are normally excluded, cross-sectional areas of through-site links are often modified as too are porous elements.

**A9. Accuracy of building model.** *The overall dimensions of the test building model (height, plan shape, etc.) should be accurate to within 2%. Architectural details, such as balconies, mullions, sun shades etc. should be included on the building model if they extend from the façade by 1 m or more.*

*The local landscape, including all vegetation, should be modelled in a current or, "as installed" growth state for pedestrian wind studies (unless the developer is prepared to install temporary protection for the trees until they reach target size). In these cases, testing should also be carried out without the effect of vegetation. Vegetation should not be included for structural or cladding load studies, or for pedestrian safety, but can be used for pedestrian comfort.*

*Surrounding buildings should be modelled with overall dimensions accurate to within at least 10% (Section A4). Architectural details need not be included on the surrounding buildings.*

Building surface roughness elements can be important in governing separation and reattachment of the wind flow, and hence special care should be taken at edges. However, the modelling of architectural details is limited by the physical size of the details, and Reynolds number effects, as discussed in A8. Immediately surrounding buildings need to be modelled reasonably accurately so that important features such as the sizes of gaps between buildings are correct. Buildings further away from the test model can be modelled by approximate block shapes.

For vegetation modelling it is important to ensure equivalence of the flow. To maintain Reynolds number requirements, modelled vegetation tends to look sparser than the prototype equivalent. The sensitivity to vegetation modelling can be examined through a "no vegetation" test. Vegetation should not be modelled for structural or cladding load studies, or pedestrian safety, as the permanence of vegetation is not guaranteed and foliage is likely to be stripped during extreme wind events.

**A10. Meteorological data.** *Wind speed data (and direction data if available), properly corrected for siting, shielding and instrument response effects, for a period not less than ten years of reliable observational data shall be used for serviceability design cases such as environmental studies and building accelerations. For extreme design studies, such as overall structural loading, or façade pressure studies, a minimum of 20 years of reliable observational data should be used.*

Wind speeds and directions given in AS/NZS 1170.2 (Standards Australia, 2011) for capital cities and defined regions in Australasia can be considered to satisfy the above criterion. For locations not covered in AS/NZS1170.2, or for other countries, the user should be satisfied that appropriate corrections have been made and that the record length is long enough. If insufficient record length is available at a single site, then a superstation approach should be considered (Peterka and Shahid 1998). In tropical cyclone affected areas, Monte Carlo simulation techniques (e.g. Vickery *et al*. 2000) may be used to supplement meteorological data in the prediction of extreme wind speeds and directions.

Either gust or mean wind speed data may be used, provided appropriate corrections are made to relate to the reference wind speed in the wind tunnel.

Early wind data (i.e. pre-1990s) in Australia were recorded by Dines anemometers, which had different response characteristics from the automatic weather stations (typically three-cup or propeller anemometers) that are currently used. The exact change-over dates should be identified, and appropriate corrections to the recorded gusts made (Holmes and Ginger, 2012). In New Zealand, heavy Munro anemometers were used prior to about the mid-1990s. Subsequently more responsive Vector and Vaisala anemometers are used, but the recorded data are averaged over 3 s. Exact changeover dates are available from NIWA.

**A11. Directionality.** *Account should be made of the varying probability of exceedance of wind speeds with wind direction.*

Directional probability calculations can be carried out in a number of ways, depending on the availability of sufficient meteorological data. These can include:

(a) A calculation of the probability of exceedance for any wind direction, from the conditional probabilities of wind speed given a wind direction and the coefficients determined from the wind tunnel for each direction. Methods of doing this have been described by a number of authors (e.g. Davenport, 1971; Melbourne, 1984; Holmes, 1990; Apperley and Vickery, 1974).

(b) Use of wind directional multipliers in Standards Australia (2011), or of data derived in an equivalent manner. The method of deriving the directional values in AS/NZS 1170.2 was given by Melbourne (1984).

(c) When directional wind information is not available, the use of an appropriate statistical reduction factor (Davenport, 1977; Holmes, 1981) may be applied to the structural response computed from the all-directions wind speeds.

**A12. Data Retention.** *The wind engineering laboratory should retain all wind-tunnel test results, and instrument calibration data for a minimum period of seven years to assist with peer reviews as required.*

## PART B. WIND-TUNNEL SURFACE PRESSURE MEASUREMENTS

**B1. Number of pressure measurement positions.** *The average pressure tap density should not be less than 1 pressure tap per 120 m² of surface area on the test building.*

The density given is a minimum average value. The local density should be higher near wall edges and discontinuities of cross-section. Higher average densities should be used for smaller buildings and complex shapes. In some cases, it may be practical to perform wind tunnel tests in multiple stages, with subsequent stage positions selected to improve the definition of the first stage results. A similar approach may be required for special studies where the presence of exposed pressure tubing would significantly influence the flow pattern around the structure. For large areas of low-pressure gradient, the average pressure tap density may be reduced below 1 pressure tap per 120 m², with justification.

**B2. Number of wind directions.** *Design pressures for individual measurement positions should be determined for at least 36 wind directions at 10° increments.*

For special studies, the requirement for 36 wind directions may be relaxed with justification, or increased for studies investigating flow phenomena that occur over narrow bands of wind directions.

**B3. Pressure coefficients and reference pressures.** *Wind tunnel pressure measurements shall be provided in the form of coefficients of peak external pressure with respect to a static (atmospheric) pressure at the building site in the absence of the building. A suitable dynamic pressure based on a gust or mean wind speed, that can be directly related to appropriate meteorological data, should also be used.*

The static pressure reference can be obtained from the static holes of a pitot-static probe mounted in a low-turbulence region of the wind tunnel away from the direct influence of any near-field building. Alternatively, it could be obtained from a probe especially designed to measure static pressure in turbulent flow conditions, or from a pressure tapping in the wall of the wind tunnel. However, possible lateral or longitudinal static pressure gradients in the wind tunnel should be investigated, and appropriate corrections made.

The dynamic pressure may also be obtained from a pitot-static probe, but the latter should not be located at a position where the longitudinal turbulence exceeds about 10%, or the reference dynamic pressure will be overestimated.

**B4. Extraneous acoustic pressure fluctuations.** *The contribution of extraneous acoustic pressure fluctuations to the total mean square pressure fluctuation for any measurement point should not exceed 5%.*

The generally incompressible pressure fluctuations generated by turbulent and separated flows around building models should be distinguished from compressible pressure fluctuations, generated as a result of wind-tunnel ductwork or other components and which are specific to a particular wind-tunnel design. Acoustic pressure fluctuations in wind tunnels can be produced by a number of sources – by vorticity generated by the fan blades, longitudinal (organ pipe) or lateral acoustic resonances, unsteady flow in diffusers or the vibration of turning vanes. Acoustic pressure fluctuations manifest themselves as spikes on the spectral densities of pressure fluctuations, or as high correlations at certain frequencies.

**B5. Frequency response.** *The amplitude frequency response of the pressure measuring instrumentation, represented by the ratio of recorded amplitude to applied amplitude of a sinusoidal pressure, should be shown to not depart by more than 10% from a constant value from 0 Hz to a frequency, in model scale, equal to* $2U_h/B$ *Hz (where* $U_h$ *is the mean wind speed at the top of the building, and B is the characteristic building model width). Low pass filtering should be applied to the pressure signal beyond the frequency range where the frequency response to the pressure signal begins to depart from a uniform response by more than 10%. The phase response should also not depart by more than 10% from a linear variation over this frequency range.*

The frequency response of a pressure measurement system depends on the geometry of the pressure tubing system and on the volume and diaphragm flexibility of the pressure transducer or sensor. A variety of techniques are available to achieve the required frequency response criteria (Holmes, 1995). The requirement for the response limit given has been well established by Durgin (1982), Holmes (1984), Irwin and Davies (1988), and Letchford *et al.* (1992), amongst others.

**B6. Digital sampling rate.** *The minimum rate of sampling of a pressure signal for digital processing should be at least three times the maximum frequency within the signal to minimise aliasing, or* $6U_h/B$*, whichever is the larger, (*$U_h$ *is the mean wind speed at the top of the building model, and B is the characteristic model width). A low pass filter should be less than half the sampling frequency to prevent aliasing in the data.*

Experience and tests have indicated that a sampling rate of three times the highest frequency in the pressure signal, is sufficient to resolve the peaks to an acceptable level of accuracy. Appropriate low-pass filtering can be achieved through analogue or digital techniques, however well-designed digital filtering may require an increased sampling rate.

**B7. Determination of peak external pressure coefficients.** *The peak external pressure coefficient for design shall be determined as the statistical average (maximum or minimum) for a defined windstorm length in full-scale (not less than ten minutes or more than three hours).*

Various methods can be used to efficiently determine the average external extreme pressure peaks – e.g. up-crossing counts (Melbourne, 1977b), sampling of maxima and minima (Peterka, 1983), determination of the extremes for shorter periods than the defined windstorm length and fitting of an extreme value distribution (Mayne and Cook, 1979). Alternatively, if the average is taken of multiple extremes in repeated identical (ergodic) experiments, no less than five time-series samples should be used.

For elements tested at a large length scale (>1:50), the spectral density cannot be fully modelled in the wind tunnel and a different testing and analysis technique should be used to estimate the peak response. Such partial turbulence matching techniques are described in Banks *et al.* (2015).

**B8. Internal pressures.** *The external pressures measured on a building model should be combined with internal pressures that have been determined according to the porosity, wall and roof openings and internal building geometry, in the prototype building.*

Internal pressures acting on a particular cladding panel depend on many factors, including porosity or leakage in the building envelope, whether intentional or unintentional, openings such as air-conditioning inlets or outlets, open windows, the distribution and porosity of internal walls and partitions, thermal (stack) effects in lift wells, etc. Usually it is not feasible to attempt to model these effects and measure internal pressures on a building model. However, conservative estimates for internal pressure coefficients to combine with the measured external pressures should be made. If there exists a possibility of openings in the building envelope occurring during wind storms (e.g. from openable windows or accidental damage), reasonable estimates of internal pressure should be made based on the probability of occurrence of such openings, or through simultaneous internal and external pressure measurements. If modelling the internal pressure in the presence of a dominant opening then proper scaling of the internal volume will need to be carried out to account for Helmholtz resonance effects.

**B9. Probability of exceedance of design pressures.** *The probability of exceedance for the design pressures on cladding shall be selected to be compatible with the design criteria of the Standard or code used to design the cladding material.*

Reference should be made to the appropriate governing document such as the National Construction Code (Australian Building Codes Board), the New Zealand Building Code, Standards Australia (2002), or NZS 4223.4:2008 for wind loading on glass.

**B10. Reporting.** *The design cladding pressures resulting from the study should be presented in a way as to simplify their interpretation for the cladding designer.*

The report for a cladding pressure study of a building should present the essential results of the study as a series of diagrams of the plan and elevations of the building, showing the design cladding pressures as zones of equal pressure. The zones may be irregular in shape, representing the actual measured pressures, or they may be rectangular in order to approximate the measured pressures in a form suitable for cladding selection and design. The zones should typically be calculated for intervals of about 0.5 kPa, with the zone pressure being equal to or greater than the predicted pressures within the zone. However, in areas that experience very strong winds, it may be more convenient to use intervals of 1.0 kPa. The zoning intervals selected should be appropriate to both the intended cladding system and the pressure gradients measured. The zone pressures should reflect the combined effects of both positive and negative peak pressures, and both external and internal pressures acting on the cladding. The individual design pressures used to prepare the zonal diagrams should also be tabulated.

In addition to the results, the report should also include sections relating to the requirements of this Manual, i.e.:

(a) A general description of the test procedure and model construction, wind tunnel and atmospheric boundary-layer simulation. Photographs of the wind tunnel model containing both the test and proximity models should be included.

(b) A description of the design wind speed analysis and consideration of directional effects.

(c) Diagrams of individual pressure measurement positions, labelled with pressure tap identification numbers.

(d) Specification of the wind directions tested, measurement duration and frequency response.

(e) The statistical analysis of the measured external pressures.

(f) Analysis of internal pressures, and the method of incorporation into the calculated design pressures.

The following additional information may be required by a client, and it is good practice to make it available:

(g) A full listing of the measured mean, standard deviation, minimum and maximum pressure coefficients for each wind direction, in either a tabulated or graphical form.

Finally, any unusual details of the study should be described. Unusual flow effects may be recorded photographically or on video.

## PART C – ENVIRONMENTAL WIND STUDIES

**C1. General.** *Sufficient information should be provided for the adequate assessment of human comfort and safety of the intended pedestrian use areas around building developments.*

Assessment methods may vary from desk studies based on fundamental principles of wind flow around isolated bluff bodies, to wind tunnel tests for more complex environments. For the latter, the use of a boundary-layer wind tunnel with acceptable methods of simulation (see Part A) is currently regarded as the most acceptable method. Computational Fluid Dynamics techniques continue to have limitations when determining gust wind speeds, or where the development is located within a suburban or urban environment (Cochran and Derickson 2011). Nevertheless, CFD may be used to supplement a qualitative desktop assessment. Guidance with regards to the appropriate use of CFD is given in Franke *et al.* (2007), Blocken (2015), and Section E4 of this manual.

Fundamental flow patterns around building configurations, and their effect on the local wind environment are described by Penwarden and Wise (1975), Aynsley *et al.* (1977).

**C2. Number of wind speed measurement positions.** *The average density of wind speed measurement positions should not be less than 1 position per 200 m² of the pedestrian accessible plan area of the development site and adjacent pedestrian thoroughfares or other outdoor areas that are accessible by occupants of neighbouring buildings, if they are likely to be impacted by the proposed development.*

From a pedestrian safety perspective, wind speed measurement positions should be concentrated at points where wind environment problems are typically known to occur, e.g. near corners, in front of exposed windward faces, and in open arcades linking windward and leeward faces. For pedestrian comfort, the intended use of the space for a specific activity (e.g. outdoor seating, swimming pool, or restaurant) should influence measurement locations. AWES (2014) recommends minimum areas to be investigated around developments. Where the site incorporates large open areas, relaxation of the above measurements position density may be acceptable. Care should be taken when modelling enclosed arcades for Reynolds number effects, see A8.

**C3. Measurement of wind speed.** *Wind-tunnel speed measurements should be made with an instrument with response characteristics to match the criteria for human comfort with which the measurements are being compared. Measurements should be expressed in the form of a ratio with a suitable reference speed that can be directly related to meteorological data.*

Wind environment assessment criteria have been expressed in terms of both gust (peak) and mean speeds. Fluctuating and peak speed measurements may be made with hot-wire or hot-film anemometers. Irwin probes may also be used (Irwin, 1981). Hot-wire or hot-film sensors are subject to errors in the mean wind speed in regions of high turbulence (Bottema *et al.*, 1992). Irwin probes are also subject to errors in regions of high turbulence, vertical flows, and with local wind-tunnel mean flows less than about 3 m/s.

Some laboratories have developed techniques for assessing the mean wind environment by recording the erosion of a bed of material using digital photography. It has been found that such techniques give repeatable results, particularly at windy locations on the windward face where the erosion occurs first. When combined with climate data, images showing the wind comfort categories based on mean wind speed can be produced.

The reference speed should be obtained from a position in the wind tunnel that is not affected by the near-field buildings under study.

**C4. Frequency response.** *When gust speed measurements are carried out, the amplitude frequency response of the measuring instrumentation should be shown not to depart by more than 10% from unity from 0 Hz to a frequency equivalent to 0.15 Hz in full scale. The phase response should not depart by more than 10% from a linear variation over this range.*

The 0.15 Hz limit corresponds approximately to a 3 second averaging time in full scale, this being the approximate response characteristic of meteorological anemometers used to measure the gust speeds on which the acceptable criteria are based. This frequency requirement can be easily met by hot-wire or hot-film anemometers and by pressure measurement techniques. For instrumentation based on pressure measurement techniques, the frequency response depends on the pressure tapping geometry, the dimensions of the connecting tubing (including any restrictors etc.), the volume and diaphragm flexibility of the pressure transducer or sensor, and on the characteristics of any pressure scanning device (e.g. ‘Scanivalve’). A variety of techniques are available to achieve the required frequency response, (e.g. Holmes, 1995), and digital corrections are appropriate, e.g. Halkyard *et al.* (2010).

**C5. Number of wind directions.** *Local environmental wind speeds should be determined for at least 16 wind directions.*

The actual directions chosen should depend on the sensitivity of the wind speeds at critical locations to direction, and on availability of directional meteorological wind speed data.

**C6. Assessment criteria.** *The assessment of the local wind environment shall be based on the criteria required by the relevant planning authority regulations. In cases where the planning authority has not specified criteria, the consultant should nominate suitable criteria, which take into account the proposed activity at the location and an appropriate level of probability of an unacceptable wind speed.*

The most widely used criteria are those by Davenport (1972), Lawson (1975, 1990) and Melbourne (1978b). Only the safety limit is usually adopted from the latter. AWES (2014) provides guidance with regards to the safety criterion. Temperature and humidity may also affect the acceptability of a given wind speed for pedestrian comfort, and these factors may also be considered in the selection of suitable criteria for a location. Other criteria and further background information on criteria development may be found in Hunt *et al.* (1976), Isyumov and Davenport (1976), Lawson and Penwarden (1976), Penwarden and Wise (1975), Soligo *et al.* (1998), Janssen *et al.* (2013), Ratcliff and Peterka (1990), and Koss (2006)

Particular care should be taken for locations situated in semi-enclosed spaces, which are treated differently to outdoor spaces from a human perception perspective. In such semi-enclosed spaces where stationary activities are intended, the use of a criterion to achieve wind conditions significantly better than the long duration stationary activities in outdoor areas is recommended. An example is the ASHRAE criterion of 1.2 m/s based on a 50 percentile wind speed.

**C7. Reporting.** *The assessment of the local wind environment for a development should be presented in a way that simplifies the interpretation for the client.*

The report should present a summary of results which indicate the suitability or otherwise of the proposed activity for the sites investigated, e.g. thoroughfare, outdoor restaurant etc.

In addition to the results, the report should also include sections relating to the requirements of this manual, i.e.:

(a) A general description of the test procedure and model construction, wind tunnel and atmospheric boundary-layer simulation.

(b) A description of the analysis for the determination of the wind climate, including analysis of directionality effects.

(c) Diagrams of measurement locations, labelled for identification.

(d) Specification of the wind directions tested, measurement sample time, and frequency response.

(e) Effects of variation in vegetation modelling (i.e. a ‘no vegetation’ study to check the sensitivity of the results to this effect).

Finally, any unusual details of the study should be described. Unusual flow effects may be recorded photographically or on video.

## PART D - WIND-INDUCED OVERALL LOADS AND DYNAMIC RESPONSE

**D1. Test objectives.** *Wind tunnel tests for overall loads and response of tall buildings shall enable accurate determination of design base bending moments and shear forces, torsional moments, effective static load distributions, and prediction of wind-induced deflections and accelerations.*

Base moments and shear forces are associated with strength design and are hence calculated using either very long return period wind speeds associated with ultimate limit states design approaches or a return period wind speed associated with a building lifetime and applying a load factor to the loads predicted. Deflections and accelerations are generally associated with serviceability design, and normally use shorter return periods. Where wind-induced vibrations of building developments are expected to be significant, assessment of accelerations with respect to occupant comfort criteria should be made.

**D2. Building dynamic characteristics.** *Sufficient information regarding the structural dynamic characteristics of the building should be provided to the wind tunnel laboratory by the project structural engineer. These must include the mode shapes and natural frequencies of at least the first three modes of vibration of the prototype building, mass and mass moment of inertia distribution, and damping characteristics for the prototype building.*

The above information, except damping, would normally be obtained from a computer model of the structure. For very tall, slender or complex-shaped buildings, the effects of higher modes of vibration may need to be considered. Damping may be estimated from code values or by reference to full-scale measurements of similar structures (e.g. Tamura *et al.*, 2000).

**D3. Methods of testing.** *Measurements shall be made by either (a) high frequency balance testing, (b) simultaneous multi-channel pressure measurement. (c) linear mode aeroelastic model testing, or (d) full aeroelastic model testing. Aeroelastic testing shall be used for cases in which reduced velocity ($U_h/n_0B$ where $U_h$ is the mean wind speed at building height, $n_0$ is the fundamental natural frequency of vibration, and B is the characteristic building width) exceeds 8 for sharp-edged building sections, 6 for hexagonal, octagonal or chamfered corner building sections, or 4 for circular or oval building sections.*

Full aeroelastic modelling is uncommon and is used only where higher order modes are likely to provide a significant contribution to the structural response. For the large majority of cases, an aeroelastic model is not required and a rigid model test (force balance or simultaneous pressure measurement technique) can be used to obtain the wind force spectrum. The force spectrum can be modified to obtain the response spectrum through the application of a mechanical admittance function (for further explanation of this see

Holmes, 2015). However, the use of a force balance is not appropriate in cases in which aerodynamic damping (displacement dependent effects) is expected to be significant or approaches the level of structural damping. High aerodynamic damping in tall buildings can occur in a low-turbulence environment (for example, facing the ocean) and where the prototype building is exposed to design reduced velocities that are more than 80% of the critical reduced velocity for the building section concerned. The limiting reduced velocities represent conditions where these simple building plan shapes will typically experience significant aerodynamic damping (Steckley, 1989).

**D4. Geometric modelling.** *The overall dimensions of the test building model, height, plan shape, etc., should be accurate to within 2%. Architectural details with a dimension of greater than 1 m, or 10% of the building width, whichever is smaller, and closer than 15% of the building width to any corner should also be modelled. The geometric scaling ratio should not be less than 1:800 and at the same time shall satisfy the requirements for minimum Reynolds Number stipulated in Section A8.*

Building surface roughness elements can be important in governing separation and reattachment of the wind flow, and hence special care should be taken at edges. However, the physical size, appropriateness from a flow modelling perspective, and the practicality of incorporating small details into the building model limit the modelling of the architectural details. A suggested lower limit to the detail of these elements would be all features that have a maximum sectional dimension of less than 1m.

**D5. Test requirements.** *The sample rate should be at least 5 times the scaled natural frequency of the building at its design wind speed. Testing should be performed for a minimum of 36 wind directions and a minimum sample period equivalent to 1 hour duration in full-scale.*

Irrespective of the sampling duration and sampling rate a sufficient data sample needs to be acquired to provide sufficient resolution in the response spectra. Finer increments of measurements can be used to investigate critical directional effects.

***D5.A High-frequency balance testing.*** *The model/balance frequency should be at least 30% greater than the scaled building natural frequency for the relevant loading direction.*

In the high-frequency balance test, the model is mounted on a very stiff balance capable of measuring the overturning moment on the model. Typically, a very lightweight model must be used, with a stiff mounting method, so that the model/balance system has a very high natural frequency (Tschanz and Davenport, 1983, Boggs, 1991).

The high-frequency balance method attempts to measure direct aerodynamic forces, but these may be distorted by the natural dynamic characteristics of the balance and model. Separating the model/balance frequency from the scaled building model frequency will minimise the errors introduced by this distortion.

***D5.B Simultaneous multi-channel pressure measurement.*** *When multiple pressure transducers are used to determine the fluctuating overall wind forces acting on a building as a combination of the fluctuating local pressures on the walls of the building, the following minimum criteria should be observed:*

*a)* *At least one pressure tap should be allocated for every 120 $m^2$ of building surface.*

*b)* *Intermediate fluctuating wind loads per unit height should be determined from at least five levels on the building.*

*c)* *The amplitude frequency response of the pressure measuring instrumentation, represented by the ratio of recorded amplitude to applied amplitude of a sinusoidal pressure, should be shown not to depart by more than 10% from a constant value from 0 Hz to a frequency, in model scale, equal to the higher of $0.5U_h/B$ Hz (where $U_h$ is the mean wind speed at the top of the building and B is the minimum building model width or $2.5 \cdot n_0$, where $n_0$ is the lowest natural frequency of the full-scale building). The phase response should also not depart by more than 10% from a linear variation over this frequency range.*

*Using this technique, the pressures must be measured simultaneously such that the phase lag between any pair of pressure taps is less than 30°.*

Extreme care should be taken to not distort the dynamic characteristics of the pressure tap/tubing/pressure transducer system (e.g. Halkyard *et al.* (2010)), and appropriate modal and area weighting factors must be established for each tap for use in the synthesis. One constraint of this pressure approach for tall buildings is the difficulty in getting enough pneumatic tubing into the model for simultaneous data collection, particularly for complex articulated facades where it would be extremely difficult to simultaneously capture the effect of these façade articulations. However, for lower buildings, there is typically ample room for sufficient tubes to accurately define the pressure distribution, and the roof uplift contribution (which may be significant for a long, low building). The high-frequency balance encompasses this addition to the base moments in a manner that may overestimate the dynamic design loads. Additionally, actual non-linear and coupled mode shapes can easily be accommodated directly in the simultaneous pressure approach.

***D5.C Aeroelastic testing.*** *For all types of aeroelastic modelling, frequency ratios between modes should be modelled to an accuracy of within 5%. Where translational mode shapes can be approximated to within 20% by a linear mode shape, a linear mode aeroelastic model may be employed. For more complex mode shapes, a full multi-degree of freedom aeroelastic model should be employed.*

If the aeroelastic model technique is used, then the rig must be set up so as to replicate the dynamic behaviour of the prototype building as closely as possible. This includes care in ensuring that if coupling effects in the prototype due to similar natural frequencies in the two translational modes occur, then the model should also have similar natural frequencies in these modes.

In the case of an aeroelastic model, care should be taken to ensure similarity between the generalised masses of the model, and those of the prototype building.

Where the centre of rotation does not match with the geometric centre of the building, care should be taken to mount the building model from the position representing the centre of rotation of the prototype building.

Linear translation modes can be modelled by (a) base-pivot rigid models or (b) rigid models mounted on a cantilever at one point.

In the case where an aeroelastic rig is used, providing a straight-line approximation to the mode shape, the position of the pivot point should be such that the straight line matches as closely as possible to the line of best fit to the mode shape of the first two modes (with emphasis on the upper sections of the tower).

**D6. Mode-shape corrections.** *Results from linear mode aeroelastic or high frequency balance tests should be corrected for mode shape where the mode shapes depart by more than 10% from the linear approximation. The effect of coupling between different axes in a given mode of vibration should be accounted for.*

There are various correction methods available for the above, e.g. Holmes (1987), Boggs and Peterka (1989), Xu and Kwok (1993), Holmes *et al.* (2003).

In the simultaneous multi-channel pressure measurement technique (Clause D5.B), non-linearity in the mode shape can be taken account of in the weighting of the pressures recorded at each height level on the structure.

**D7. Response combination.** *The simultaneous effects of wind loading and response in two orthogonal directions, as well as torsional loading and response, shall be taken account of in design.*

Direct wind forces and resonant dynamic response generate effective loads in both along-wind and cross-wind directions on tall buildings, as well as torsional moments. These act simultaneously and should not be treated as separate independent load cases. If the frequencies of sway in two orthogonal directions are well separated, then the responses in the two directions will be poorly correlated statistically. One approach for the combination of translational load effects, when there is little or no coupling, or correlation, between orthogonal responses, is described by Holmes (2015), (Section 9.6). Several other methods are in use including graphical approaches.

Full aeroelastic tests (Section D5.C) have the capability of reproducing any coupling between orthogonal modes if the correct relationship between the respective frequencies on the prototype structure is retained. The combination of simultaneous pressure measurement techniques (Section D5.B) and advanced structural engineering design software will increasingly allow this rigid wind tunnel model technique to be used to assess coupling effects. Dynamic coupling effects are not reproduced with high-frequency balance testing (Section D5.A). However, the frequencies of the constructed buildings are often different from those estimated by the structural engineer at the design stage, and coupling effects, which usually mitigate resonant dynamic response by transferring energy between orthogonal modes, are unpredictable and difficult to confidently reproduce in any wind tunnel model.

**D8. Serviceability acceleration assessment.** *Serviceability accelerations shall be assessed to ensure that risk of complaint resulting from wind-induced building motion is kept to within a suitable criterion.*

Complaints about wind-induced building motion may arise from occupants being alarmed by the motion during extreme wind events, or being annoyed by frequently perceptible motion (Denoon, 2000). The acceptability criteria for a particular project will depend on the proposed use of the structure, whether it will be occupied during severe wind events, the likely reaction of occupants to perceptible wind-induced motion, the wind climate and the dynamic characteristics of the structure. Commonly used sets of guidelines are ISO6897-1984, ISO10137:2007. The ISO6897-1984 guidelines were extended to peak accelerations and different return periods by Melbourne & Cheung (1988) and these values are presented in AWES (2011). Recent research such as that by Kwok *et al*. (2009) has shown that the human response to building motion is frequency dependent. Criteria such as those by the NBCC are considered limited, as they are independent of the natural frequency of vibration of the structure, while the ISO6897-1984 and ISO10137:2007 guidelines are frequency dependent, a factor that has been found by many studies to be important in the determination of motion perception and tolerance. Whichever guidelines are used, it should be recognised that they are guidelines rather than strict criteria and some flexibility in their application is acceptable as long as the implications for an altered risk of complaint are recognised.

Torsional acceleration should be converted into an equivalent translational acceleration and added into the combined acceleration with due consideration of the degree of correlation between the accelerations along the three principal axes between vibration modes.

**D9. Effective static load distribution.** *The base moments determined from an aeroelastic or high-frequency balance study shall be distributed over the structure in a rational and consistent way.*

In general, the effective static wind loads arising from the mean, background (quasi-static fluctuating), and resonant components of wind loading on a tall building, are distributed differently from each other as a function of height, (e.g. Holmes and Kasperski, 1996; Holmes, 2001). The background loading distribution depends on the type of load effect (e.g. base shear or moment), and its location on the structure. However, if the resonant component is dominant over the background component, it is acceptable to approximate the combined fluctuating load distribution with an effective inertial loading as a function of height. The latter is proportional to the mode shape of the structure. Conversely, if the background response is dominant, the effective static wind loading may be taken as that for the background base bending moment.

The distribution of the mean component with height based on the distribution of the mean pressure coefficients with height along the windward and leeward faces for the most critical wind direction. The distribution of the dynamic component with height based on either a linear variation from the pivot point to roof level (adjusted to account for the effect of variations in the width of the tower), or the inertial moment.

It is important to ensure that the loading distributions assumed produce values of mean and fluctuating base bending moments equal to those measured on, or predicted from, the wind-tunnel tests. The process of integrating the mean pressure loads from a simultaneous pressure test to compare with the mean high-frequency balance loads, or aeroelastic test results, as a function of wind direction is a useful quality assurance tool.

**D10. Reporting.** *The assessment of wind-induced loads and vibrations for a development should be presented in a way that simplifies the interpretation for the client. In addition, the maximum total standard deviation and peak combined horizontal accelerations should be presented and compared with the criteria.*

The report should present a summary of results, which indicate the overall design base moments, and corresponding accelerations for serviceability design. In addition, the corresponding point load and shear force distribution with height should be provided. The report should present as a minimum the assumed dynamic properties as well as the directional mean and background standard deviation moment coefficients.

If the mode shape presents a significant departure from the straight-line mode shape, the mode shape correction factor adopted should be discussed.

In discussing buildings accelerations, the maximum total standard deviation and peak combined accelerations should be compared to acceleration acceptability guidelines as described in Section D.7.

## PART E - OTHER STUDIES

Besides the Wind Engineering Studies outlined in the previous sections, there are other types of studies that may be used to supplement those already discussed. Some of these are briefly outlined below. This section is entirely *informative* and provides no *normative* requirements as provided in Parts A – D. The reader is encouraged to seek further guidance if undertaking any of these tests.

### E1. Wind Tunnel Prototype Tests

These are normally performed at 1:1 scale and used to test building components for lift and drag, discharge coefficients (effective area ratio), or wind noise. In the case of a wind noise test the sample must be supplied by the client to ensure that the test accurately represents the final product as method of connection, material, dynamic properties, precise gaps and machining can influence results. For large models, where it is not practical to use a 1:1 scale model, 1:2: to 1:10 scale models may be used with suitable matching of modelling parameters. However, the use of scale models should be carefully considered. Often the fluid mechanics being investigated are not the same on geometrically scaled models compared to full scale, so the observations obtained may not be valid. Careful consideration should also be given to the wind tunnel blockage for prototype testing as this will significantly influence the performance of the prototype.

It should be appreciated that when testing at full-scale, the turbulence structure created in the wind-tunnel is markedly different in terms of frequency content from that experienced in the real world and the impact of this on the results should be clearly stated.

### E2. Wind Tunnel Section Model Tests

These are normally carried out at large scales of between 1:100 and 1:10. These tests are performed to test aerodynamic performance of large industrial components, or to determine wind loads on façade elements such as sunshade devices that cannot be tested at smaller scales. Section model tests may also be required in cases involving ventilated double-skin facades, although care should be taken to properly scale the internal volume for Helmholtz resonance effects.

As with E1, the frequency content of the incident wind reproduced in the wind tunnel needs to be documented and suitable appreciation of the impact of departures in the frequency spectrum with respect to the full-scale should be clearly stated.

### E3. Dispersion Studies

These are normally performed in the wind tunnel for point, line or area sources. Flow visualization may be used to assist in the case of a preliminary qualitative assessment or to provide general design guidance. However, flow visualization should not be used to determine quantitative data for dispersion studies. A trace gas, coupled with measurements of concentrations at various critical locations is required in the case where quantitative results are required for comparison against exposure standards. Froude Number similarity needs to be satisfied in these types of studies.

## E4. Computational Fluid Dynamics (CFD)

Computational fluid dynamics (CFD) needs to be used with caution in external turbulent flow environments (Franke *et al*. 2007, Blocken 2015). Current capability falls short in the case where the modelling of local gust (or gust-equivalent means) wind speeds for the assessment of pedestrian safety and comfort. The accuracy of CFD for this application has not yet advanced to the point where it can be reliably used to check against accepted comfort criteria. It should be noted that for a number of steady-state turbulence models, the 'mean' CFD output is an area averaged mean and does not model the transient nature of turbulence in the flow, i.e. it smears the wind conditions in the shear layer. The consequence of this is that a 'mean' CFD result would not necessarily agree with a time-averaged mean from a physical model. Primarily, CFD has its application for modelling of internal flow, buoyancy effects or air quality when coupled with wind tunnel data for the boundary conditions.

CFD can be suitably benchmarked against the results of physical modelling. However, extrapolation should be conducted with care. CFD can also be combined with the results of physical modelling in a hybrid fashion. The two approaches both have strengths and weaknesses in certain applications and one may be used to reinforce the other. For example, the wind-tunnel data for a slender building with excessive accelerations may be used to "calibrate" a CFD model. That computer model may then have architectural shape changes explored many times via CFD until a viable solution is found. The new design should then be confirmed in the wind tunnel.

As stated in Section A1, CFD is not yet capable of reliably determining peak design loads on structures. However, notwithstanding the above discussion, any wind related CFD study should conform with all components of the study as descried in this document in terms of modelling the atmospheric turbulent boundary layer across the test domain, wind climate analyses, and the appropriate number of wind directions for each particular study.

## E5: Wind shear and Turbulence testing at Airports

Wind tunnel studies can be conducted to assess the impact of wind shear and turbulence on aircraft operations. General background is provided in Nieuwpoort *et al.* (2010). For airports in Australia, NASF Guideline B (NASF, 2018) defines the wind shear and turbulence criteria and provides guidance for assessment, mitigation, and modelling.

In terms of local wind speed measurements, the principles outlined in Part A are applicable for these wind tunnel studies. The length scale for testing should be as large as possible. It is important to ensure the stability of the boundary layer wind shear and turbulence profiles across the test domain are maintained. Measurement should be taken with suitable anemometry equipment capable of measuring turbulent length scales equivalent of 1-2 s full-scale. The test measurement locations and wind directions are outlined in Guideline B and should be taken with and without the subject building for direct comparison. Measurements outside the assessment zone in Guideline B should be considered for longer runways. The results should be analysed in such a way as to be readily interpreted for aircraft operations at the specific airport, i.e. a 3 s gust measured at the airport anemometer.

The wind tunnel test report should include:

- presentation of the mean wind speed and turbulence profiles, and spectral density in the boundary layer upstream and downstream of the test section relative to the target values, to illustrate the stability of the modelled wind field,
- description of the test procedure and instrumentation including calibration,
- data acquisition parameters (sampling frequency, sample duration, and any details of filtering or signal conditioning),
- description of the subject building or structure, including photographs of the wind tunnel model,
- diagram of the test point layout and wind directions tested, and
- tables showing 3 s gust wind speed required at the airport anemometer to exceed the various criteria as described in Guideline B.

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