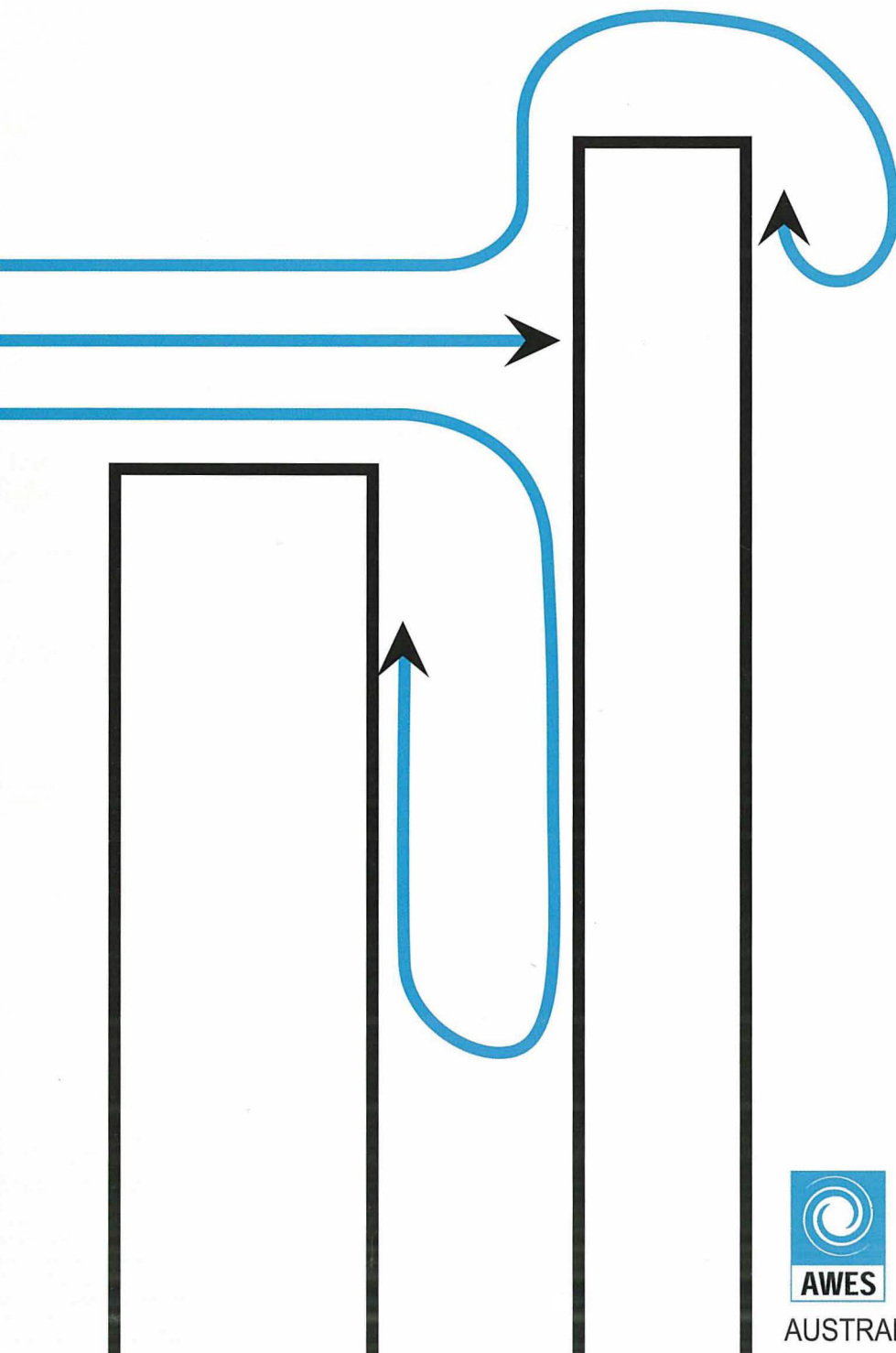


WIND LOADING HANDBOOK FOR AUSTRALIA & NEW ZEALAND

Background to AS/NZS 1170.2 Wind Actions



AWES-HB-001-2012

**WIND LOADING HANDBOOK FOR AUSTRALIA
AND NEW ZEALAND
Background to AS/NZS 1170.2 Wind Actions**

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Preface

Recent wind events in Australia and overseas have caused catastrophic results in those affected areas, with deaths being reported as well as widespread destruction. Research and information gathered from these events have been incorporated into the latest edition of AS/NZS 1170.2 – 2011 to now represent a more realistic determination of wind actions. The Standard applies to structures ranging from *'the less sensitive to wind action to those for which dynamic response must be taken into consideration'*.

This Handbook was prepared by the AWES to provide background information into wind and its actions, but also into the derivation of the Standard and its contents. It covers items such as:

- Nature of wind loading
- Wind speeds and multipliers
- Shape factors for structures
- Dynamic response

In particular, it equips users with a better understanding of wind and the Standard to provide them with improved interpretation and judgment in determining wind actions on structures.

Equally important, it enables the user to extend the Standard limitations while still complying with regulations, albeit other information may be necessary.

It must be borne in mind: the user is ultimately responsible for their design, notwithstanding the Standard, and this Handbook *exists to assist the user as far as practicable to discharge those responsibilities in the best interests of the project, the owner and the community.*

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Disclaimer: *While all due care has been taken in the collection and preparation of information in this Handbook, no responsibility is assumed by the Australasian Wind Engineering Society, or the individual authors or contributors, for any consequences arising from the use of it.*

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1: INTRODUCTION, HISTORY AND SCOPE

1.1 INTRODUCTION

This Handbook is intended to support and supplement the Australian/New Zealand Standard for Wind Actions, AS/NZS 1170.2:2011. It provides background for the clauses in the Standard. In addition, it provides additional information on shape factors and dynamic factors, such as structural damping, – i.e. information that is compatible with, but not provided in, the Standard itself. Although it performs the functions of a commentary, this Handbook does more than that; however, there is no direct clause-by clause correspondence with the Standard itself.

This document is a successor to the ‘Commentary to AS 1170.2-1989’ published by the Australian Wind Engineering Society (Holmes, Melbourne and Walker, 1990), which performed a similar function for the 1989 Australian Standard.

The Handbook is divided into the following chapters and appendices:

Chapter 1 gives an introduction to wind loading, a history of the Standard, and includes background on *Sections 1* and *2* of the Standard itself.

Chapter 2 discusses wind speeds and multipliers incorporating background to *Sections 3* and *4* in AS/NZS 1170.2.

Chapter 3 provides background on *Section 5* in the Standard – i.e. shape factors for rectangular enclosed buildings. Additional information for designers is given – particularly on attachments to buildings.

Chapter 4 covers shape factors for structures other than rectangular enclosed buildings, and includes commentary on *Appendices C* to *F* in the Standard.

Chapter 5 discusses the dynamic response of structures to wind and provides background to *Section 6 – Dynamic response factor*, in the Standard.

Appendix A provides a more detailed discussion of structural damping than that given in Chapter 5, and Appendix B provides a comprehensive list of references and a bibliography.

References to clauses, figures, tables etc. in AS/NZS 1170.2:2011 are given in *italics* in this Handbook. References to sections, figures and tables in the Handbook are not in italics.

1.2 NATURE OF WIND LOADING

Wind loading of structures is a complex phenomenon. The wind itself is random, being composed of a multitude of eddies of varying sizes and rotational characteristics carried along in a general stream of air moving relative to the Earth's surface. These eddies give wind its gusty or turbulent character. In both Australia and New Zealand, extreme winds can be produced by a variety of mechanisms.

In Australia, extreme winds which are important in the design of structures can be classified as 'synoptic' winds and small-scale thunderstorm events. Synoptic winds are produced by large-scale pressure systems – essentially a balance between Coriolis forces associated with the earth's rotation, and pressure gradients. These storms may last for several days. In Tasmania and the South Island of New Zealand, located in the latitudes known as the 'roaring forties', gales produced by large-scale synoptic events are common. These also affect the southern coastline of Australia. Along the eastern coast of New South Wales, strong winds are often produced by 'East Coast Lows' – low pressure systems in the Tasman Sea.

Tropical cyclones are a particular type of severe synoptic storm that occur over the tropical ocean. In the Northern Hemisphere they are also known by the names of 'hurricanes' and 'typhoons'. In Australia they affect extensive lengths of the coastlines of Queensland, the Northern Territory and Western Australia. In recent decades, information gained from satellite imaging, and aircraft flights in other countries, has greatly improved knowledge of these events. In many events, relatively little definitive information on the wind speeds produced when tropical cyclones make landfall in Australia is available, due to the sparseness of anemometers.

For synoptic winds, the gustiness of strong winds in the lower levels of the atmosphere, known as the 'boundary layer', arises from frictional interactions with surface features such as vegetation, buildings and water surfaces, which characterize the terrain. In the lower levels of the boundary layer, in which most structures are located, the wind speed averaged over time periods of ten to sixty minutes generally increases progressively with height, while the gustiness, or turbulence, tends to decrease with height. The average wind speeds are also affected significantly by topography, such as hills, escarpments and ridges.

Thunderstorms are driven by strong convection of warm moist air to high altitudes. Rapid cooling is accompanied by the release of latent heat. This energy re-appears as kinetic energy of falling rain, hail and cold air. The downdraft of cold air generates an outflow gust front at ground level. The maximum gust from these events near the ground can exceed 50 m/s.

Along the coastal strip of south-eastern Australia, convective thunderstorms and severe downdrafts are usually associated with cold fronts. However, in northern and inland Australia, severe storms are produced by local convection. Although relatively little is known about the variation of gust wind speeds with height in these events, the gust profile at time of the peak winds appears to increase slowly up to about 100 metres height, reducing in magnitude at greater heights; however, the gusts are well correlated (or

synchronized) over large distances horizontally, resulting in significant wind loading on horizontal, line-like structures such as transmission lines. The period of strong winds is much shorter than for synoptic events. An appropriate averaging time for winds in convective downdrafts is about 1 minute. The turbulence, or gustiness, superimposed on the average wind is lower than that for synoptic events, as the effects of terrain and surface roughness are much lower. Topography is also expected to have a lesser effect on wind gusts from downdrafts, compared with that on synoptic winds.

New Zealand, particularly in the South Island, experiences 'downslope' winds on the lee side of the Alps. These are associated with gravity waves above the mountain peaks. They can produce sustained winds for several hours but affect relatively small areas.

When strong winds interact with a structure, pressures and forces on the surfaces of the structure are generated. The characteristics of these pressures are influenced by the characteristics of the approaching wind and the geometry of the structure. Significant internal pressures may also be generated if there are openings, or permeability, linking the exterior of a building with the interior.

Pressures on structures are not steady, but highly fluctuating, partly because of the gustiness in the wind, but also because of local eddies and vortex generation at the edges of the structures themselves. The pressures are also not uniformly distributed spatially over the surface of a structure.

Most of the effects described in this section are incorporated into the Standard in some form or other, but mostly in an approximate, or generalized way. The complexities of wind loading described here, should be kept in mind when applying a design document like the Australian/New Zealand Standard. Due to these many uncertainties, the maximum wind loads may vary from those assumed in design. It should also be noted that the actual strength of a structure, or its elements, when constructed, may differ considerably from that assumed at the design stage. Thus non-failure of a structure due to wind cannot necessarily be taken as evidence of conservatism of the wind actions Standard.

1.3 HISTORY OF AUSTRALIAN AND NEW ZEALAND STANDARDS ON WIND LOADING

1.3.1 History of Australian Standards

AS/NZS 1170.2:2011 has a lineage that goes back forty years. Australian Standard CA34, Part II published in 1971 (Standards Association of Australia, 1971) replaced an earlier interim document, and was the first modern wind loading code or standard published in either Australia or New Zealand. Although in Imperial units, all subsequent Australian and New Zealand Standards are directly descended from it. It contained a contour map of 'regional basic wind speeds' in miles per hour with a 50-year return period (applicable to most structures), using anemometer data analyzed by Whittingham (1964). As in all subsequent versions, this wind speed was defined as a gust of 2-3 seconds duration

recorded at the standard meteorological height of (33ft.) 10 m in flat open, terrain. However, recent research has found that the averaging time of the peak gust, recorded by the Dines anemometer used at that time, was considerably less than 2-3 seconds – see Section 2.4.2.

CA34 Part II also gave a table of ‘regional basic design’ wind velocities for 5, 25, 50 and 100-year return period values for 48 cities, towns and other centres, for which the wind speed analyses had been carried out. Values for a number of these stations were labeled ‘short record’. Notably, considering the event that occurred three years later, the value given for Darwin for 100-year return period was only 119 mph (53 m/s). However, a ‘cyclone factor’ of 1.15 was applied to all locations north of 30°S within 30 miles of the coastline. The four terrain categories specified were essentially the same as those given in the current Standard. Shape factors (pressure and force coefficients) were all given in an Appendix and were largely based on the British Code of Practice and Swiss Norm of the time, with values obtained in smooth-flow wind tunnels. However, local pressure factors of 1.5 and 2.0 were specified in edge and corner regions – but with no tributary area restrictions. A section on dynamic response was provided, but this largely offered descriptive and reference material.

AS 1170.2 – 1973 (Standards Association of Australia, 1973) was essentially a metric version of CA34, Part II -1971, although some changes to the listed regional basic wind speeds were made for some stations. Dynamic response of tall buildings was covered only in an informative Annex (in fact – extracts from a conference paper by B.J. Vickery).

The occurrence of Cyclone ‘Tracy’ at Darwin, on Christmas Day in 1974, resulted in a new version of AS 1170.2, with a change to the map of regional basic design wind velocities. A zonal system for the cyclone-prone coastal strip of northern Australia was introduced. Also in the 1975 edition (Standards Association of Australia, 1975) an increased value of negative pressure coefficient for cladding elements on side walls of tall buildings was recommended in a note. An amendment, released in 1978, introduced a new table of external pressure coefficients for the roofs of buildings with pitches less than 10 degrees. This was later incorporated into the 1981 edition of AS 1170.2 (Standards Association of Australia, 1981).

In the 1983 edition of AS 1170.2 (Standards Association of Australia, 1983), the widely-used table in *Appendix B* of external pressure coefficients for pitched roof buildings was extensively revised to include values obtained in turbulent flow from a boundary-layer wind tunnel. In addition, an area reduction factor for roofs according to tributary area, a wind direction reduction factor, a new system of moving areas for local pressure factors and revised rules for wind flow over escarpments, were introduced. However, the majority of AS 1170.2-1983 was similar in format and content to CA34, Part II-1971.

The 1989 edition of AS 1170.2 (Standards Australia, 1989) was a major revision of earlier versions. It was introduced as part of the conversion to limit states design in Australia. It also attempted to provide an alternative simpler approach for smaller low-rise buildings, and to provide a more accurate determination of wind loads for tall structures with significant dynamic response. AS 1170.2-1989 consisted of three ‘stand-alone’ sections as follows:

Section 2. Simplified Procedure

Section 3. Detailed Procedure: Static Analysis

Section 4. Detailed Procedure: Dynamic Analysis

Each section had its own map of regional wind speeds (pressures in the case of the Simplified Section), and multipliers for terrain and topography. A new feature of the 1989 Standard was the specification of high-return-period design wind speeds (i.e. 1000 years) for ultimate limit state design. This eliminated the need for the 'cyclone factor' in earlier versions. This concept has since been adopted in the United States.

The 1989 Standard also contained numerous other changes with revisions to shape factors for multi-span buildings, free-standing walls and roofs, and building frames reflecting the extensive research carried out in the 1970s and 1980s. The cross-wind response of tall buildings was also incorporated in detail (possibly for the first time anywhere in the world).

AS/NZS 1170.2:2002 (Standards Australia, Standards New Zealand, 2002a) was the first combined Australian/New Zealand wind actions Standard and was also a major revision in format compared to AS 1170.2-1989.

The following major changes were also introduced in 2002:

- A variable annual probability of exceedence was adopted for wind speeds. These replaced importance multipliers used in AS 1170.2-1989,
- The separate 'simplified procedure', and 'detailed procedure: dynamic analysis', used in AS 1170.2-1989 were removed, and a single design method based on a gust wind speed was adopted,
- Direction multipliers for wind speeds for all non-cyclonic regions were introduced, replacing directional wind speeds for capital cities only in AS 1170.2-1989,
- Methods based on mathematical formulae were introduced for calculation of hill-shape (topographic) multipliers and for cross-wind dynamic response of tall buildings,
- The methods for dynamic response used for along- and cross-wind dynamic response in AS 1170.2-1989, were replaced with approaches based, as the rest of the Standard, on a peak gust wind speed.

In addition, numerous smaller changes, additions and adjustments to the tables of shape factors were incorporated.

For the first time in its history, the 2002 edition of the Standard was later supplemented by a user-friendly Guide (Holmes and King, 2005), containing nine detailed examples of application of the Standard to various types of structure.

The 2011 edition of AS/NZS 1170.2 had a number of significant changes and additional clauses have been incorporated. The principal changes are as follows:

- A torsional loading requirement in *Clause 2.5.4* in the form of an eccentricity of 20% of the breadth, b , applied to the along-wind loading. This has only been prescribed

for tall buildings greater than 70 metres in height (see Section 1.6.6 in this Handbook).

- Windborne debris impact loading criteria have been added in *Clause 2.5.7*.
- New wording in *Clause 5.3.2* requires designers to treat closed doors and windows, particularly roller doors, as potential dominant openings unless it can be demonstrated that they are structurally capable of resisting the design wind loads.
- A new *Clause 5.3.4* requires consideration of wind loads on internal walls and ceilings.
- A revised version of *Clause 5.4.3* concerned with the action combination factor
- Some changes to *Clause 5.4.4* and *Table 5.6* on local pressure factors.

In an Amendment to AS/NZS 1170.2:2011, based on recent research on the wind profiles in tropical cyclones and hurricanes, it is proposed to remove *Table 4.1(B)* – i.e. the terrain/height multipliers in Regions C and D will be the same as those specified for Regions A and B. Furthermore, the terrain category for over-water winds will generally be treated as Terrain Category 1, irrespective of limit state (i.e. on the level of wind speeds), or of the region. However, for winds blowing from an ocean fetch, the inshore region of breaking waves may be treated as an intermediate Terrain Category 1½.

1.3.2 Previous New Zealand Standards

Prior to 2002, New Zealand had separate loading Standards dated 1984 and 1992. The wind loading section (Part 5) of NZS 4203:1992 (Standards New Zealand, 1992) was in fact an adaption of, and very similar to, AS 1170.2-1989. The main differences were in the different treatment of topographic effects and multipliers, and the lack of a dynamic analysis method for wind loading. However, NZS 4203:1992 referred the user to AS 1170.2-1989 for the latter.

In 2002, in common with many other standards, a combined Australia-New Zealand Wind Actions Standard was published. The use of common standards has resulted from the Closer Economic Relations (CER) free trade agreement between the two countries dating back to the 1980s. The seven wind regions for New Zealand in NZS 4203:1992 were simplified to three regions in AS/NZS 1170.2:2002. Also the ‘limit-state multipliers’ used in NZS 4203, to adjust wind speeds for serviceability and ultimate limit states, were discontinued. Instead average recurrence intervals were used in AS/NZS 1170.0:2002 (*Section 3*) as a basis for determining regional wind speeds for design in New Zealand.

1.4 SCOPE, AND DETERMINATION OF WIND ACTIONS

Clause 1.1 of the Standard limits the coverage to buildings less than 200m in height and roof spans less than 100m. ‘Roof spans’ should be interpreted as ‘unsupported roof spans’. In the case of tall buildings greater than 200 metres in height, the dynamic effects are more significant and complex than can be handled by the Standard. In both these cases, wind-tunnel studies and related processing is normal practice. Offshore structures, bridges and transmission line towers are also excluded. In the case of the last two, separate Australian

and New Zealand standards which incorporate wind load information are available. In the case of bridges in Australia, the Bridge Design Standard is AS 5100 (Standards Australia, 2004). For overhead line design, an Australian – New Zealand Standard, AS/NZS 7000:2010 was issued in 2010 (Standards Australia/Standards New Zealand, 2010).

The effects of tornados are also excluded in *Clause 1.1*. In Australia, only about sixteen confirmed tornados occur on average each year, over the whole country. The risk of a direct strike on an individual structure is minimal; however a structure designed to satisfy AS/NZS 1170.2 should perform satisfactorily in weaker tornados – i.e. Categories F1 and F2 on the Fujita scale.

Direct application of AS/NZS 1170.2 is one method of determination of wind actions, and is the recommended method by the Building Code of Australia. However, there are other alternative paths, or ‘special studies’, that provide an equivalent level of confidence, and are regarded as acceptable:

- Reliable references used consistently with the clauses of AS/NZS 1170.2.
- Reliable data on wind speed and direction corrected for the influence of terrain, topography and neighbouring buildings where necessary, including a detailed probabilistic analysis for the effects of wind direction.
- Wind tunnel tests carried out for a specific structure, or reference to such tests on a similar structure, together with applicable clauses in AS/NZS 1170.2.
- Calculations by computational fluid dynamics, *which have been calibrated against full-scale or wind-tunnel measurements.*

Wind-tunnel testing in Australia and New Zealand should normally follow the procedures of the Quality Assurance Manual of the Australasian Wind Engineering Society (AWES, 2001). In particular, wind-tunnel testing to determine the effects of synoptic winds shall ensure that the appropriate terrain categories are modelled, and the variation of wind speed with height, and the scale and intensity of turbulence are modelled with reasonable accuracy. Where curved shapes are involved, the effects of Reynolds number should be taken into account (this usually excludes the use of model-scale testing at low wind speeds for structures with circular cross sections, such as chimneys). Measurement systems for force and pressure should have appropriate frequency-response characteristics. When a high-frequency force balance approach is used for tall buildings, state-of-the art methods for mode shape correction and assessment of torsional response should be adopted. When modelling is adopted to directly determine resonant dynamic response and/or aeroelastic effects, appropriate scaling of mass, stiffness and structural damping should be adopted. Finally, when internal pressures are included in studies for buildings, appropriate scaling of internal volumes should be adopted (Holmes, 2006; Sharma *et al.*, 2010).

Wind-tunnel tests are also often carried out for cases that *are* covered in the Standard. Such tests can generally be expected to give lower design wind loads than the Standard. However, even if that is not the case, the results from the wind-tunnel studies should be used in preference to the values from the Standard.

1.5 UNCERTAINTIES IN ESTIMATION OF WIND LOADING

In the determination of wind loads, various parameters are combined – regional wind speeds, multipliers for terrain, topography and shielding, aerodynamic shape factors, and in some cases, a dynamic response factor. Table 1.1 gives estimations of the coefficients of variation for these variables.

Table 1.1. Estimated coefficients of variation for parameters used in AS/NZS 1170.2

Parameter	V_{25}		V_{500}	
	Region A	Other Regions	Region A	Other Regions
V_R	0.07	0.12	0.12	0.20
M_d	0.05	0.05	0.05	0.05
$M_{z,cat}$	0.10	0.10	0.10	0.10
M_s	0.20	0.20	0.20	0.20
M_t	0.15	0.10	0.15	0.10
C_{fig}	0.15	0.15	0.15	0.15
C_{dyn}	0.10	0.10	0.10	0.10

The greater uncertainty for the regional wind speeds (V_R) for Regions B, C and D reflects the fact that tropical cyclones are generally too infrequent for analyses of anemometer data to be able to make accurate predictions. There is more uncertainty in the specified values of topographic multipliers in Region A, because of the uncertain effects of topography on winds at ground level produced by thunderstorm downdrafts and outflows.

The general problems of codification for various aspects of wind loads, and the variations between national and international codes and standards were discussed in a series of papers by Holmes *et al.*, (2005a), Tamura *et al.* (2005b), Holmes *et al.* (2005b), Letchford *et al.* (2005), and Kaspersky and Geurts (2005).

1.6 DESIGN WIND PRESSURES, FORCES AND LOAD CASES

1.6.1 Design wind pressures

Equation 2.4(1) in the Standard is the basic equation for design wind pressures acting on a building surface (external or internal). This equation is reproduced in Eqn. (1.1).

$$p = (0.5\rho_{air})[V_{des,\theta}]^2 C_{fig} C_{dyn} \quad (1.1)$$

In this equation, the dynamic wind pressure $(0.5\rho_{air})[V_{des,\theta}]^2$ represents the additional pressure generated when the wind flow is brought to rest at a point in the flow, *without* the disturbance produced by a large bluff body, – it results from the conversion of momentum in the flow to a force per unit area, and essentially it is a statement of Newton's Second Law.

The value of air density, ρ_{air} , of 1.20 kg/m^3 , specified in *Clause 2.4.2* of the Standard, is an average value based on a temperature of 21°C , and typical atmospheric pressure at sea level. Locations at high altitudes such as alpine areas have lower atmospheric pressure which would lead to lower air densities, but they also tend to have a lower temperature than sites at sea level – this is a compensatory factor.

Buildings and most other ground-based structures are aerodynamically ‘bluff’, rather than streamlined. The effect of the bluff body on the pressures and forces induced by the wind is represented by the aerodynamic shape factor, C_{fig} . This normally takes a positive value on a windward wall surface, but negative values on leeward and side walls. For detailed explanations of wind flow around bluff bodies, the reader should consult textbooks on fluid mechanics, or general texts on wind effects of structures (e.g. Aynsley, Melbourne & Vickery, 1977; Cook, 1985, 1990; Holmes, 2007; Simiu & Scanlan, 1996). Aerodynamic shape factors, and associated factors like local pressure factors, used in AS/NZS 1170.2, have normally been derived from wind-tunnel studies, with some input from full-scale measurements on structures, when they are available. Aerodynamic shape factors are covered in detail in Chapters 3 and 4 of this Handbook.

The main function of the dynamic response factor, C_{dyn} , is to allow for possible resonant amplification effects on certain flexible structures with low natural frequencies. However, for the majority of structures that do not fit into this category, C_{dyn} may be taken as 1.0. The dynamic response factor is discussed in Chapter 5 of this Handbook.

1.6.2 Wind directions

Most of the aerodynamic shape factors provided in the Standard are given for four nominal orthogonal wind directions. Exceptions are free-standing walls and hoardings (*Appendix C*), individual structural members, and lattice towers (*Appendix E*), for which oblique wind directions are also required to be considered. As outlined in *Clause 2.3*, the orthogonal wind speeds are taken as the *largest site wind speed within a 90 degree sector* (i.e. +/- 45 degrees), centred on the nominal wind direction. This process is illustrated in *Figures 2.2* and *2.3* in the Standard, and discussed in more detail in Chapter 2 of this Handbook.

1.6.3 Frictional drag

Wind pressures on a building surface can generally be assumed to act normal to the surface (but not necessarily parallel to the wind direction). However, for some situations, the Standard (*Clauses 2.4.2 and 2.5.3.2; Section D2.2 in Appendix D*) requires account to be taken of the frictional drag, i.e. the component parallel to the surface. Those cases are: the walls and roof of buildings that are very long in the direction parallel to the wind, and freestanding roofs of low pitch. Frictional drag should be considered in conjunction with normal wind pressures on columns, exposed roof beams, barges, flashings etc.

1.6.4 Ultimate and serviceability limit states

Unlike AS 1170.2-1989, in which specific wind speeds for ultimate and serviceability limit states were specified, AS/NZS 1170.2:2002 and AS/NZS 1170.2:2011 do not specifically refer

to these design limit states. However, AS/NZS 1170.0 (Standards Australia/Standards New Zealand, 2002b) in *Section 2* discusses them in some detail.

For ultimate limit states design, the designer should refer to one of three sources to determine the importance level of the structure being designed:

- the Building Code of Australia (BCA) for buildings in Australia (Australian Building Codes Board, 2011),
- *Section 3* of AS/NZS 1170.0 for structures in New Zealand,
- *Appendix F* of AS/NZS 1170.0 for non-BCA structures in Australia.

Once the importance level is selected, tables in the above documents give the annual probability of exceedence (I/R). Then, *Table 3.1* in AS/NZS 1170.2 can be used to determine the appropriate regional wind speed, V_R , for design. *Table F2* in AS/NZ1170.0 allows a variation in 'design working life' to be considered; however the BCA does not recognize 'temporary structures', or allow any adjustments for design working life.

It should be noted that the BCA is only concerned with buildings and life safety, and does not consider serviceability limit states. However, guidelines for serviceability limit states are provided in AS/NZS 1170.0, and in various material standards.

Suggested serviceability limit states criteria (e.g. deflection limits) associated with an annual probability of exceedence of 1/25 are given in *Table C1* of AS/NZS 1170.0. However, these should not be regarded as exclusive. For example, acceleration limits for wind-induced vibration of tall buildings are available elsewhere, including *Section 5.9* of this Handbook.

1.6.5 Fatigue

Fluctuating wind forces can produce fatigue damage, and occasionally failures, in different ways. High-cycle fatigue – with an effective cycle count of 10^5 or more - can produce failures of steel structures with wind-induced stresses below the yield stress. This is relatively common for structures such as lighting poles, and is usually accompanied by resonant dynamic response, which can greatly increase the cycle count at higher frequencies. Simplified methods of estimating fatigue life for structures subjected to along-wind dynamic response have been described by Holmes (2002a), Robertson *et al.* (2004) and Repetto and Solari (2009). However, up to now, design methods for wind-induced fatigue have been regarded as too complex, and requiring further research, before they can be included in the Standard.

Cyclonic events have produced 'low-cycle' fatigue failures on roof and wall cladding, with a cycle count typically less than 10^4 . Failures typically have occurred in areas of stress concentration around fasteners. As stated in *Section 2.5.5* in the Standard, Part 3 of AS 4040 (Standards Australia, 1992) and the Building Code of Australia both specify test regimes for acceptable performance of cladding and fastener systems for use in cyclone-prone regions. These may change in the future following extensive research by Henderson (2010), using more realistic time histories of fluctuating roof pressures.

The Eurocode (British Standards Institution, 2005, *Figure B.3*) provides a relationship between the number of times a stress is reached or exceeded in a period of 50 years, and the stress range in a normalized form – i.e. as a percentage of the largest value in a 50-year period. This relationship is insensitive to the site or location, and could be applied in Australia or New Zealand for fatigue analyses.

1.6.6 Torsion

Wind loading can produce eccentric loading which results in a torsion about a vertical axis around a centre of stiffness of the building. This can be produced in a number of ways:

- non-uniform distribution of wind pressures, for example when the wind blows obliquely to the walls of a building,
- fluctuating loading due to turbulent gusting in the wind,
- dynamic torsion resulting from non-coincidence of the centre of mass of the building with the centre of stiffness.

The following information on the effective eccentricity of wind loading on some actual tall buildings was provided by a wind-tunnel group:

- Regular 6:1:2 aspect ratio 180m tall building: $0.18b$
- Oblong shaped plan with a radiused corner 200m tall with a stepped elevation: $0.19b^*$
- Irregular plan shape but prismatic tower 130m tall (generally 6:1:3): $0.18b^*$
- Regular 3:1:3, 60m high: $0.14b$
- Regular 3:1:3, 80m high: $0.17b$
- Twisting irregular plan (truncated aerofoil) 164m high (generally 6:1:3): $0.23b^*$
- Aerofoil-shaped plan, 130m tall (generally 6:1:3): $0.22b^*$

* these building forms strictly do not fall within the scope of AS/NZ 1170.2

Hence, the 2011 edition of the Standard, in *Clause 2.5.4*, has introduced a torsional requirement in the form of eccentricity of the resultant force arising from along-wind loading. The eccentricity is given as 20% of the cross-wind breadth (b) of the building. This requirement is restricted in AS/NZS 1170.2 to rectangular enclosed buildings of 70 metres height or greater. However, this height limit should not be taken to imply that torsional wind loading does not exist on other structures, or buildings of lower height (e.g. Tamura *et al.*, 2003).

Peak torsion on buildings generally occurs at the same time as the peak along-wind force due to the location of the centre of pressure. Cross-wind forces are generally not as well correlated with torsional moments.

1.7 WINDBORNE DEBRIS

The 1989 edition of AS 1170.2 (*Clause 3.4.7*) introduced a requirement that 'in cyclonic regions, windows shall be considered as potential dominant openings, unless capable of resisting impact by a 4 kg piece of timber of 100 mm × 50 mm cross section, striking them at any angle at a speed of 15 m/s'. This statement replaced a simple warning in the 1983 edition ('possible debris effects also may require attention'). The 1989 requirement reflected concern by the standards committees of the time about the devastating effects of windborne debris in several tropical cyclones from the 1970s onwards (e.g. Cyclone Althea' in 1971 and 'Tracy' in 1974). Creation of dominant openings in buildings by windborne debris had in many observed cases resulted in high internal pressures leading to roof failures, and in some cases complete destruction of buildings. The 2002 edition (AS/NZS 1170.2:2002), in *Clause 5.3.2*, extended the requirement from 'windows' to the 'building envelope' (windows, doors and cladding).

The 4 kg timber missile and its test speed was conceived in the 1970s in Darwin following Cyclone 'Tracy' (Darwin Reconstruction Commission, 1975). However, at that time, very little research had been available on the actual speeds reached by timber roofing members or other windborne debris in cyclones. Of course, although distance travelled by such missiles can be determined in post-disaster surveys, it is usually not possible to quantitatively determine impact speeds during such inspections.

In the early 2000s, extensive research in the United States on missile speeds in hurricanes was undertaken. One of the key conclusions of this research is that the horizontal missile speed is directly related to the horizontal distance travelled. A key paper in establishing horizontal missile speeds as a ratio to the wind gust speeds, in such events, is that by Lin *et al.* (2007). This research was based on extensive experimental tests (wind-tunnel and full-scale tests using a Hercules aircraft) and numerical simulations.

It is noted that the results of the above research on missile trajectories has been adopted in a new Standard for Storm Shelters, ICC 500, recently published in the United States (International Code Council, 2008), and the Design Guidelines for Queensland Public Cyclone Shelters (Department of Public Works, Queensland, 2006).

Clause 2.5.7 incorporates the same 4 kg timber missile as specified in the 1989 and 2002 editions; in addition, a smaller 2 gram steel ball is specified. Furthermore, the horizontal missile speeds for both missiles are specified as 0.4 times the regional wind speed; lower vertical missile testing speeds are specified.

For Region C, the horizontal missile speed is therefore 0.4×69 m/s or 27.6 m/s – considerably higher than the 15 m/s (resultant) speed previously specified. However, the research by Lin *et al.* (2007) clearly indicates that a missile speed of 15 m/s in a windstorm producing 69 m/s gusts will be attained in a very short distance of travel – less than 2 m in fact. 50% of the wind gust speed is reached in a travel distance of 7-8 m, a distance typical of the spacing between buildings in urban areas.

The horizontal trajectory missiles apply to surfaces which are subject to positive pressure (i.e. walls, steeply pitched roofs). The vertical trajectory missiles apply to surfaces on to which falling objects may land (i.e. roofs).

The 4 kg timber missile with a 100 × 50 mm cross section is the dominant impact load. The 2 g steel ball missile is 8 mm diameter and has been included to ensure the building envelope has a resistance to small windborne debris. Test specifications and acceptance criteria are defined in the Queensland Guidelines and the US Standard on Storm Shelters. Both documents require the test missiles to impact at right angles to the surface. The Queensland Guidelines requires a test specimen to be impacted by the timber missile followed by impact by five steel balls at different locations. More detailed criteria for the performance of building facades in windborne debris tests are also available in a standard published by the American Society for Testing Materials (ASTM, 2009).

The impact force applied to the building depends not only on the missile mass and speed, but also on the stiffness of the building at the impact location. The stiffer the impact location, the greater the impact force. Tests on the debris resistance of building elements have shown that the critical location is often near a support.

Debris screens can be used to protect windows from windborne debris. For a debris screen to provide full protection to a window, the maximum aperture in the screen would need to be less than 8mm. If larger aperture screens are used which resist the 4 kg missile, then the glazing or insect screen would need to be capable of resisting the 2 g missile. The gap between the debris screen and the glazing has to be sufficient to ensure that when impacted the screen deflects without breaking the glazing. The screen should either return to the wall or overlap the wall around the window, to prevent the missile breaking the glazing from an oblique impact. Guidance on debris screen geometry is provided in the Queensland Guidelines.

Current building standards do not require the external fabric of a building to be resistant to windborne debris, unless the building internal pressure is to be reduced in accordance with *Clause 5.3.2*, i.e. ignoring the possibility of a dominant opening. The vulnerability of people sheltering within their homes in the cyclone-affected regions of Australia would be greatly reduced if they had a room within the dwelling constructed to resist cyclonic winds and windborne debris.

Note that *Clause 2.5.7* is not itself a requirement for debris resistance. It merely specifies the types and speeds of the missiles when debris resistance is specified elsewhere. The latter may include *Clause 5.3.2* of the Standard, which is a requirement for internal pressures in cyclonic regions, or a requirement for shelter rooms or buildings in cyclone regions – which may be required by building owners or legislation.