15 Wind loading codes and standards

15.1 Introduction

Wind loading codes and standards, although a relatively recent concept (almost all have been produced since World War II), have achieved wide acceptance, and are often the practising structural engineer's only contact with information for wind loading calculations. Although often based on extensive research, they are, by necessity, simplified models of wind loading. Thus great accuracy cannot be expected from them. Often this is consistent with the knowledge of the structure of the windstorms themselves in their country of use. The growth of world trade is expected to reduce the number of loading standards in use, and gradually force more consistency in their format and content.

Advanced wind loading codes and standards invariably contain the following features:

- A specification of a basic or reference wind speed for various locations, or zones, within a jurisdiction. Almost always a reference height of 10 m in open country terrain is chosen.
- Modification factors for the effects of height and terrain type, and sometimes for: change of terrain, wind direction, topography, and shelter.
- Shape factors (pressure or force coefficients) for structures of various shapes.
- Some account of possible resonant dynamic effects of wind on flexible structures.

This chapter reviews the wind loading provisions of several prominent national, multinational and international documents, and highlights their similarities and differences. As codes and standards are continually being revised and updated, the overview is, by necessity, time-dependent.

Other comparisons between major wind loading codes and standards have been made by: Cook (1990), Mehta (1998), and by Kijewski and Kareem (1998) for dynamic effects.

15.2 General descriptions

The following six standards will be described in this chapter:

- ISO 4354 – Wind actions on structures – published in 1997
- ENV 1991-2-4. Eurocode 1. Part 2.4 Wind Actions – published in 1994
- ASCE Standard ASCE 7-98. Minimum Design Loads for Buildings and Other Structures – published in 1998
- AIJ Recommendations for Loads on Buildings – published in 1993
- Australian Standard AS1170.2 – published in 1989
- British Standard. Loading for Buildings. Part 2. Code of practice for wind loads. BS6399: Part 2 – published in 1997

The documents reviewed were those current at the time of writing.

15.2.1 ISO/DIS 4354 – Wind actions on structures

ISO International Standard 4354 – Wind Actions on Structures, published by the International Organization for Standardization, was issued in 1997, after remaining in draft form for many years. As described in the introduction to ISO 4354, the document is intended not as an operating standard, but as a guideline for drafting national codes of practice.

The Standard follows closely the format of the National Building Code of Canada. However, no detailed design basic wind speeds are listed, but guidelines are given for converting wind speeds from one averaging time to another, in particular to the recommended averaging time of 10 min. The main part of the document is quite short, and consists largely of definitions of the terms in the expression used to calculate wind pressure:

$$w = (q_{ref})(C_{exp})(C_{fig})(C_{dyn}) \tag{15.1}$$

A 'Simplified Method' and a 'Detailed Method' of analysis are given. The latter is intended for dynamically wind-sensitive structures, and includes resonant effects in the determination of C_{dyn}. Several annexes describe these quantities in more detail, and give 'representative' values for C_{exp}, C_{fig}, and C_{dyn}. The data on the aerodynamic shape factor, C_{fig}, have been reproduced from the National Building Code of Canada and from a former Swiss Norm (of 1956). As stated in the Introduction to ISO 4354, the data in the annexes are 'only examples and are not intended to be complete'.

The special characteristics of hurricanes (tropical cyclones and typhoons), and of thunderstorm winds have also not been considered. This document is not intended as a replacement for national wind loading standards – i.e. it is not a usable code of practice, but rather as a descriptive guidebook for the main features of a wind loading code.

15.2.2 ENV 1991-2-4. Eurocode 1. Part 2.4 Wind actions

This draft edition of Eurocode 1 on wind loads is a European Pre-Standard (ENV) which is intended for experimental application, and for the submission of comments. However it represents several years of work by representatives from many countries of the European Union, and is the nearest document to a truly multinational wind loading standard currently in existence. In its final form, this code will be mandatory throughout the E.E.C. and replace all existing national documents.

Distinction is made in the document between 'Principles' (denoted by the letter P), comprising general statements, definitions, requirements and analytical models for which there is no alternative, and 'Application Rules' for which it is permissible to use alternatives provided they accord with the relevant Principles.

This is a lengthy document with comprehensive methods of static and dynamic design for wind loads. Basic wind speeds are provided separately for no less than than eighteen European countries in an annex. The basic wind velocity is a 10-min mean velocity at 10 m height in open country terrain, with an annual probability of exceedence of 0.02 (50-year return period).

15.2.3 ASCE Standard ASCE 7-98. Minimum design loads for buildings and other structures

ASCE 7-98 is a complete loading standard covering all types of loads, and the wind loading part (Section 6 and its associated commentary) is a relatively small component of the whole document.

The 1995 and 1998 editions incorporated a number of significant changes in the wind load provisions from the 1993 and earlier editions. This includes the use of a 3-second gust wind speed instead of the 'fastest-mile-of-wind' as used in the past, a new zoning system for basic wind speeds, the incorporation of topographic factors, some new data on pressure coefficients, a simplified procedure for buildings less than 9 m in height, and a revised method for along-wind dynamic response calculation.

The ASCE Standard has no legal standing of its own, but its provisions are cited by many of the regional, city and county building codes. The three major regional building codes in the U.S. will shortly merge to form a single 'International Building Code'. This presumably will draw on the ASCE Standard for wind load provisions.

15.2.4 AIJ Recommendations for loads on buildings

The Recommendations of the Architectural Institute of Japan were revised in 1993 (English language edition published in 1996) and are a comprehensive loading code including the effects of dead, live, snow, seismic, temperature, earth and hydraulic pressure, as well as wind loads. Chapter 6 on wind loads comprises twenty pages, with thirty pages of commentary. The derivation of the wind loading section of the AIJ are described in detail by Tamura *et al.* (1996).

Like the ASCE Standard, this is a comprehensive and advanced wind loading document, although the recommendations have no legally binding standing in Japan. The Building Law of Japan has a separate set of simplified wind loading rules.

15.2.5 Australian Standard AS1170.2

The current edition of the Australian Standard for Wind Loads was issued in 1989 in a substantially revised form from previous editions. It is a comprehensive document of ninety-six A4 pages, and is supported by a separate commentary published by the Australian Wind Engineering Society (Holmes *et al.*, 1990).

AS1170.2 has an indirect legal status by being called up in the Building Code of Australia, which itself is called up by the building regulations of the individual states of Australia. The wind loading provisions of the New Zealand Loading Standard NZS4203 have been derived directly from AS1170.2, and other small South Pacific nations, such as Fiji, make some use of the Standard.

The basic wind speed in AS1170.2 is a 3-second gust measured at 10 m height in open country terrain, and values are specified for ultimate and serviceability limit states, and permissible stress, for four regions of the country. The risk of exceedence for the serviceability and ultimate limits wind speeds are 5% in 1 year and 50 years, respectively, corresponding to return periods of 20 and 1000 years.

15.2.6 British Standard BS6399: Part 2: 1997

Part 2 of the British Standard BS6399 – Loading for Buildings is the 'Code of practice for wind loads' which replaced CP3: Chapter V: Part 2 in 1995. The significant difference between BS6399: Part 2 and the earlier code of practice is that the basic wind speed is an hourly mean, instead of the 3-second gust speed used in earlier editions. However, the mean wind speed is subsequently converted into a gust speed for calculation of design loads, to take advantage of the quasi-steady model of wind loads. The stated reasons for using the hourly mean are: that it allows more accurate treatment of topography, and that it provides a starting point for calculations involving fatigue and dynamic response.

BS6399: Part 2 provides two alternative methods of calculating wind loads: (1) a 'standard method', which does not use directional wind speed and coefficient data; and (2) a 'directional method', which is more complex but generally less conservative.

In this comparison the standard method only will be discussed, as the other standards do not have equivalent methods to the directional method.

15.3 Basic wind speeds or pressures

Table 15.1 summarizes the basic wind speed characteristics used, or recommended, in the six documents. In all cases the standard meteorological reference position of 10-m height in flat, open country is used.

The ISO Standard, as previously discussed, does not give basic wind speeds or dynamic pressures. However, it provides a useful conversion method between wind speeds averaged in four different ways, and the 10-min velocity pressure, q_{ref}, used as a basis for calculation of wind loads (see equation 15.1).

The European pre-Standard ENV-1991 gives 'reference wind velocities', $v_{\mathrm{ref},0}$, for 18 countries in Europe in an informative annex. For many of these countries, maps with either regions, or isotach contours, are given. For the smaller countries, a single wind velocity is specified. Although these are nominally 10-min mean wind speeds, there are clearly inconsistencies and discontinuities at the boundaries between some countries. For some countries, 3-second gust wind speed or hourly-mean data only are available. The annex also contains country-specific rules on topography, terrain roughness, etc.

The American Standard (ASCE-7) contains maps with two zones in the majority of the country, and closely specified contours for Alaska and the coastal regions adjacent to the Gulf of Mexico and the Atlantic Ocean. In the latter case, the effects of hurricanes are of particular concern. The values of basic wind speed given on these maps, are peak gust wind speed, with an annual probability of exceedence of 0.02. The methodology for the derivation of the basic wind speed maps for the United States has been described by Peterka and Shahid (1998).

The Recommendations of the Architectural Institute of Japan (AIJ) gives a detailed map showing contours of the basic wind speed (10-min mean with 100-year return period). Single values are given for outlying territories such as Okinawa.

In the Australian Standard, a basic wind speed is given in the form of a map with four regions, denoted by A, B, C and D. Two of these regions (C and D) comprise a coastal strip exposed to the effects of tropical cyclones (Section 1.3.2). Three separate basic wind speeds are specified for each region for design by permissible stress methods, serviceability

Table 15.1 Definitions of basic wind speeds

Code	*Averaging time*	*Return period (s)*
ISO 4354	10 min	50 years
ENV 1991-2-4	10 min	50 years
ASCE 7-98	3 s	50 years
AIJ	10 min	100 years
AS1170.2	3 s	20, 1000 years
BS6399: Part 2	1 h	50 years

and ultimate limit states. These correspond approximately to gust wind speeds with 20-year, 50 year and 1000-year return periods, respectively. The analysis of extreme wind speeds for the 1989 Australian Standard was described by Dorman (1983, 1984). The probabilistic basis for the limit-states-design wind speeds were discussed by Holmes (1985).

In the British Standard, BS6399.2:1997, the basic wind speed, V_b, (1-h mean) is given in a map, which covers Ireland as well as the United Kingdom. This has an annual risk of exceedence of 0.02, i.e. a 50-year return period.

15.4 Modification factors on wind velocity

All the documents include modifiers for the effect of terrain/height and topography, although in the case of ISO 4354 and ASCE 7–98, these act on the dynamic *pressure*, rather than wind *speed*. The Eurocode modifiers on wind speed, for terrain and height (roughness coefficient, c_r) , and for topography, c_t, are squared and multiplied by another factor, involving turbulence intensity, to form an exposure factor c_e, which then is used with the dynamic pressure (see Section 15.5). This factor effectively converts the *mean* dynamic pressure into a *gust* dynamic pressure at the height of interest.

ENV 1991-2-4, AS1170.2 (for regions not affected by tropical cyclones) and BS6399:2 use a logarithmic law (or a modification for gust speeds) to define the terrain/height variation, ASCE 7-98 and AIJ use a power law variation, and ISO 4354 suggests the use of either, and gives parameters for both. AS1170.2 allows for changes of terrain upwind of the site, with an interpolation of terrain/height multipliers. The British Standard allows for this indirectly through an allowance for the distance of the site from the sea.

AS1170.2 has special 'terrain-height multipliers' for regions C and D affected by severe tropical cyclones. These reflect the steeper profiles with lower gradient heights characteristic of tropical cyclones (Section 3.2.5).

ASCE 7-98 and AS1170.2 also have importance factors or multipliers; in the case of ASCE 7-98, this acts on the pressure rather than on speed. The AIJ recommendations give a return period conversion factor, and ISO 4354 also has this facility, but not as an explicit factor.

The Australian Standard, AS1170.2, is unique in having a 'shielding multiplier', which allows for reductions in velocity when there are buildings upwind of greater or similar height.

The British Standard BS6399: Part 2 has a number of unique features in relation to the calculation of the design wind speed: an 'altitude factor', (S_a), which depends on the height of the site above sea level and a 'seasonal factor', S_s. The 'terrain and building factor', S_b, includes an allowance for the distance of the site from the sea, as discussed previously; it also incorporates a gust factor to convert the hourly mean wind speed to a peak gust wind speed. A 'site wind speed' is calculated by multiplying the basic wind speed, V_b, by factors for altitude (S_a), wind direction (S_d), season (S_s) and probability (S_p). The seasonal factor, S_s, may be used to reduce loads for temporary structures that are exposed to wind loads for defined periods less than a year. The altitude factor incorporates the aerodynamic effects of topography, as well as the increase of wind speed with height above sea level.

Table 15.2 summarizes the formats for calculation of design wind velocities and dynamic pressures in various documents. ISO 4354 is alone in calculating a basic dynamic pressure from the basic (unfactored) wind velocity. Variation with height and terrain, topography, etc., is incorporated at the stage of calculating building pressure.

Table 15.2 Calculation formats for velocity, dynamic pressures and building pressure

Code	*Velocity*	*Dynamic pressure*	*Building pressure/force*
ISO4354	V	$q_{ref} = (1/2)\ \rho V^2$	$w = (q_{ref})\ (C_{exp})\ (C_{fig})\ (C_{dyn})$
ENV1991-2-4	$v_{ref} = c_{DIR} c_{TEM} c_{ALT} v_{ref,0}$	$q_{ref} = (1/2)\ \rho v_{ref}^2$	$w_e = q_{ref} c_e(z)\ c_{pe}$
ASCE 7-98	V	$q_z = (1/2)\ \rho K_z K_{zt} K_d V^2 I$	$p = q\ (GC_p)$
AIJ	$U_H = U_o E_r E_g R$	$q_H = (1/2)\ \rho U_H^2$	$W_f = q_H C_f G_f A$
AS1170.2-1989	$V_z = VM_{(z,cat)} M_s M_t M_i$	$q_z = (1/2)\ \rho V_z^2$	$p_e = C_{p,e} K_a K_\ell K_p q_z$
BS6399: Part 2	$V_e = V_b S_a S_d S_s S_p S_b$	$q_s = (1/2)\ \rho V_e^2$	$p_s = q_s C_{pe} C_a$

15.5 Building external pressures

Table 15.2 also shows the general format for calculation of external pressures on wall or roof surfaces of enclosed buildings.

The formulas (in the right-hand column) appear to be quite different from each other, but they all contain quasi-steady or mean pressure coefficients (C_{fig}, c_{pe}, C_p, C_f, $C_{p,e}$, C_{pe}) and factors to adjust the resulting pressures to approximate peak values. In the case of ISO 4354 and AIJ, they are gust factors on pressure (C_{dyn} and G_f); in the case of the Eurocode, the function is incorporated in the exposure coefficient $c_e(z)$ which also includes terrain/height and topographic effects through the relationship:

$$c_e(z) = c_r^2(z) c_t^2(z)[1 + 2gI_v(z)] \tag{15.2}$$

where $c_r(z)$ and $c_t(z)$ are roughness and topography coefficients, respectively. $I_v(z)$ is the turbulence intensity.

The term in square brackets can be regarded as a gust factor on pressure.

In ASCE 7-98, the quantities G and C_p are usually combined together as (GC_p) in Tables. In AS1170.2, the local pressure factor K_ℓ, is always greater than 1, and the area reduction factor K_a, which allows for correlation effects over large areas in separated flow regions, is less than one. AS1170.2 is alone in having a factor (K_p) for porous cladding.

The tables of shape factors and pressure coefficients of exterior surfaces of buildings given in the various documents are also sources of significant differences. However, in all cases the nominal wind directions are normal to the walls of buildings of rectangular plan. However, as previously discussed in Section 15.2.6, the British Standard has a directional method, which incorporates pressure coefficients for 15 degree direction increments.

ISO 4354 gives graphs of $C_{fig} C_{dyn}$ for the cladding on walls and roofs, and the frames of low-rise buildings (widths $>2 \times$ height, and height <15 m) with flat and gabled roofs. There are strong similarities between these figures and ones for GCp for buildings less than 18 m height in ASCE-7-98. Both documents give graphs of shape (and gust) factor as a function of tributary area. There are numerical differences however, such that the values in ASCE-7-98 are 50–60% of those in ISO 4354. This is because, as shown in Table 15.1, ASCE uses a 3-second gust wind speed rather than a 10-min mean. However, since $(\bar{U}_{10\mathrm{min}}/\hat{U}_{3\mathrm{sec}})^2$ is 0.35–0.40, it appears that ISO 4354 will give peak loads on low-rise buildings about two-thirds of those specified in ASCE-7-98. However, ASCE-7-98 allows a further reduction of up to 15% through the use of a 'wind directionality factor', K_d. ISO 4354 does not consider any variation of load with terrain for low-rise buildings designed by the 'Simplified Method'.

The tables in ISO-4354 and ASCE-7-98 for low-rise buildings do not allow for variation with height-to-width ratio. However, an alternative figure for C_p in ASCE-7-98 (for buildings of all heights), which has been derived from equivalent tables in Australian Standard AS1170.2 does allow for the variation with height/width ratio. The ASCE-7-98 Standard has incorporated some post-1989 amendments to AS1170.2 which require alternative positive roof pressure coefficients to be considered. These are important values for the design of frames, especially for those in colder climates where dead loads are often high, as pointed out by Kasperski (1993).

ENV-1991-2-4 gives Tables of external pressure coefficients c_{pe} which are comparable to those in ASCE-7-98 and AS1170.2, since they are effectively applied to gust dynamic pressure through the use of the exposure coefficient $c_e(z)$. The Tables give two values: $c_{pe,1}$, intended for tributary areas less than 1 m^2, i.e. local cladding design, and $c_{pe,10}$ intended for major structural members. It appears that the numerical values for flat and gable ('duopitch') roofs in ENV-1991-2-4, are comparable to those in ASCE-7-98 and AS1170.2, however again no variation with height/width ratio is given, and no alternative (positive or lower negative) values are given for roof pitches less than 15 degrees.

The values of shape factor in the Australian Standard AS1170.2 for flat and gable-roofed buildings have already been discussed. However, it should also be mentioned that the effect of tributary area is dealt with by the use of the two factors: K_ℓ (local pressure factor) and K_a (area reduction factor).

The AIJ recommendations also separate the specification of loads on the structural frames and on the 'components and cladding' of buildings. The specification of pressure coefficients is separated from the specification of the gust factor, G_f. Unlike any of the other documents, the gust factor for the loads on the frames of low-rise buildings has a dependency on natural frequency (Detailed Method II). Buildings are classified as those with heights less than, or greater than 45 m, a somewhat greater height than used in the other documents.

The 'size effect factor', C_a, in the British Standard BS6399 Part 2, is specified in a graph. It depends on the diagonal dimension of the 'load-sharing area', with a minimum value of 5 m. When overall loads involving wind pressures on both windward and leeward facing surfaces, are being calculated, a reduction factor of 0.85, to allow for the 'non-simultaneous' action between faces, is allowed.

15.6 Building internal pressures

The treatment of internal pressures varies considerably from one document to another. ISO 4354 gives a general description of the nature of internal pressures, and then suggests ranges of $C_{fig,i}$ for three situations: buildings with large openings, buildings with small openings not uniformly distributed, buildings with small openings uniformly distributed.

ENV 1991-2-4 gives a graph of c_{pi}, varying from +0.8 to –0.5, as a function of an opening ratio, μ, and then suggests values from that graph, for a number of particular opening situations. This document also gives fairly detailed guidance on pressures on walls and roofs, with more than one skin.

ASCE 7-98 specifies three different situations: open. partially enclosed, and enclosed buildings, and specifies values of GC_{pi} between +0.55 and –0.55. A feature, not found in the other standards, is a reduction factor, R_i, for large building volumes.

AS1170.2 gives five situations with various positive and negative values of $C_{p,i}$. For one of these cases, the values depend on the ratio of dominant openings on the windward wall to the total open area on other walls and roof.

The AIJ recommendations does not specify a positive internal pressure, i.e. the possibility of dominant openings is not considered. For buildings without dominant openings, values of C_{pi} of 0 or –0.4, with a gust effect factor of 1.3 are specified.

In the British Standard, only three possible cases are specified, and these also do not include the possibility of a dominant opening, with a large positive internal pressure.

15.7 Specified pressure coefficients for roofs

As a series of examples for comparison of shape factors or pressure coefficients, the specification for various kinds of medium to large roofs of low-rise buildings by the various codes, will be considered. The following cases will be examined:

(a) A flat or near-flat roof for an enclosed building with a square planform, and wall height to width ratio of 0.2. Nominal width and height are 25 m and 5 m, respectively.
(b) As for (a), but a free-standing roof or canopy, i.e. the space under the roof is assumed to be open
(c) As for (a), but with an arched roof with a rise-to-span ratio of 0.2
(d) As for (c), but for a domed roof on a circular planform with a rise-to-span ratio of 0.2.

As discussed in Section 15.3, some of the Standards under review are based on wind speeds with mean wind speeds averaged over 10 min or 1 h, and conversion to peak velocities or to peak pressures is accomplished by means of gust factors or an exposure factor (ENV-1991-2-4). Thus the basic pressure coefficients discussed following are ultimately factoring a gust pressure, and are thus directly comparable with each other. However, the method of dealing with area averaging effects varies considerably between the documents, as previously discussed. For example the Australian Standard (AS1170.2) has an 'area reduction factor', K_a, based on the tributary area of the structural system; in the present comparisons, this area will be taken as the total plan area of the roof. The British Standard specifies a 'size effect factor', C_a, which depends upon the diagonal dimension of the tributary area, and also on the terrain and height.

The comparisons will be separated into the loads in major structural members, and loads on small elements of cladding. In these comparisons, external pressures only will be considered for the enclosed buildings. Internal pressures are an important part of the net pressure, but are much less dependent on the building shape, being mainly affected by the number and size of openings in the building envelope.

15.7.1 Case (a) Square plan enclosed building with flat roof

The effective pressure coefficients for the structural loads on the roof are given in Figure 15.1, and for areas of cladding of the order of 1 square metre are given in Figure 15.2. In Figure 15.1, K_a in the Australian Standard is taken as 0.8, and C_a in the British Standard is 0.85. In the case of the American (ASCE) Standard, Figures 6-4 and 6-5B have been used to obtain values of GC_p.

Figure 15.1 shows that the largest magnitude negative pressure coefficients, which occur at the windward end of the roof, are reasonably similar in magnitude in all the codes; however the zoning systems are quite different to each other. The American (ASCE-7-98) and International (ISO 4354) Standards give very similar pressure coefficients to each other for structural loads. The British Standard and the Eurocode also give similar values to each other. Only AS1170.2, ENV-1991-2-4 and BS6399.2 allow for the possibility of positive pressures occurring on the leeward half of the roof, and only AS1170.2 allows

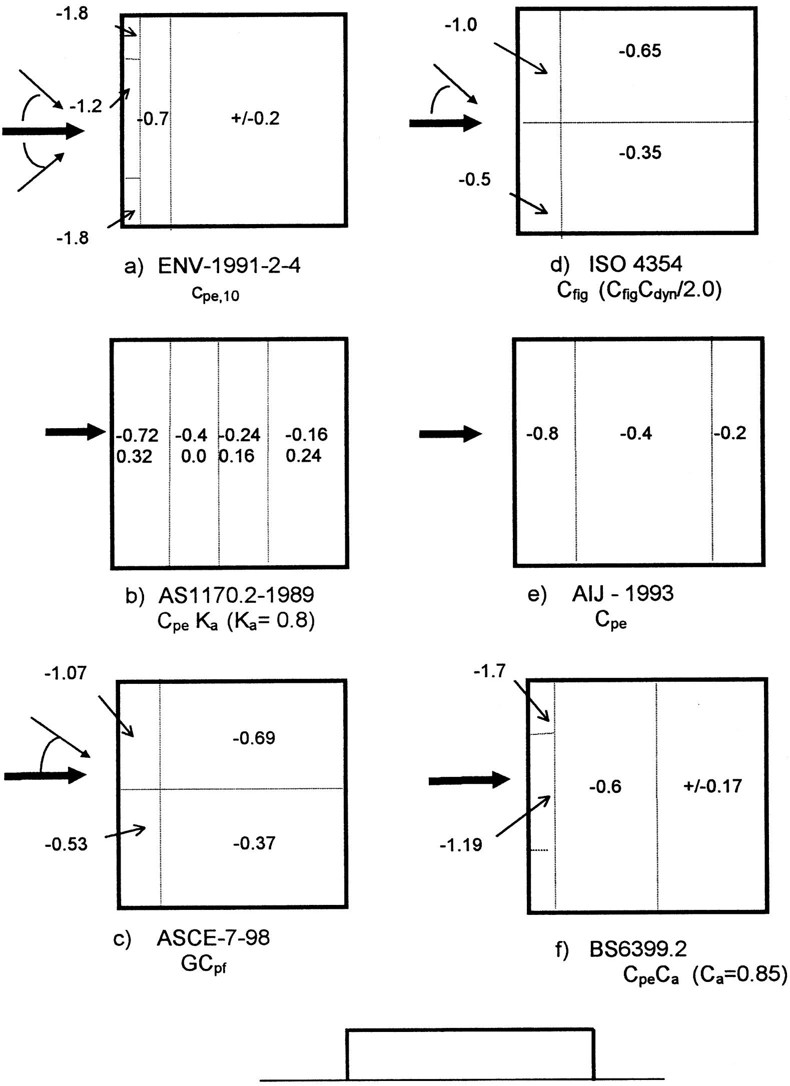

Figure 15.1 Comparison of pressure coefficients for a flat roof (main structural loads) $h/d = 0.2$.

for alternative negative pressures on the windward end. As discussed in earlier chapters, the nature of the fluctuating and turbulent flow over large roofs can produce large fluctuations in the instantaneous pressures acting.

There are bigger differences in both the zonal system and the specified pressures for small areas of cladding between the various codes, as shown in Figure 15.2. All the codes specify higher pressures along the edge regions of the roof, i.e. the regions mainly affected by the separated flow from the walls. All except the Australian Standard (AS1170.2) give higher pressures at the corners, with the largest values being specified by the Eurocode and the American Standard.

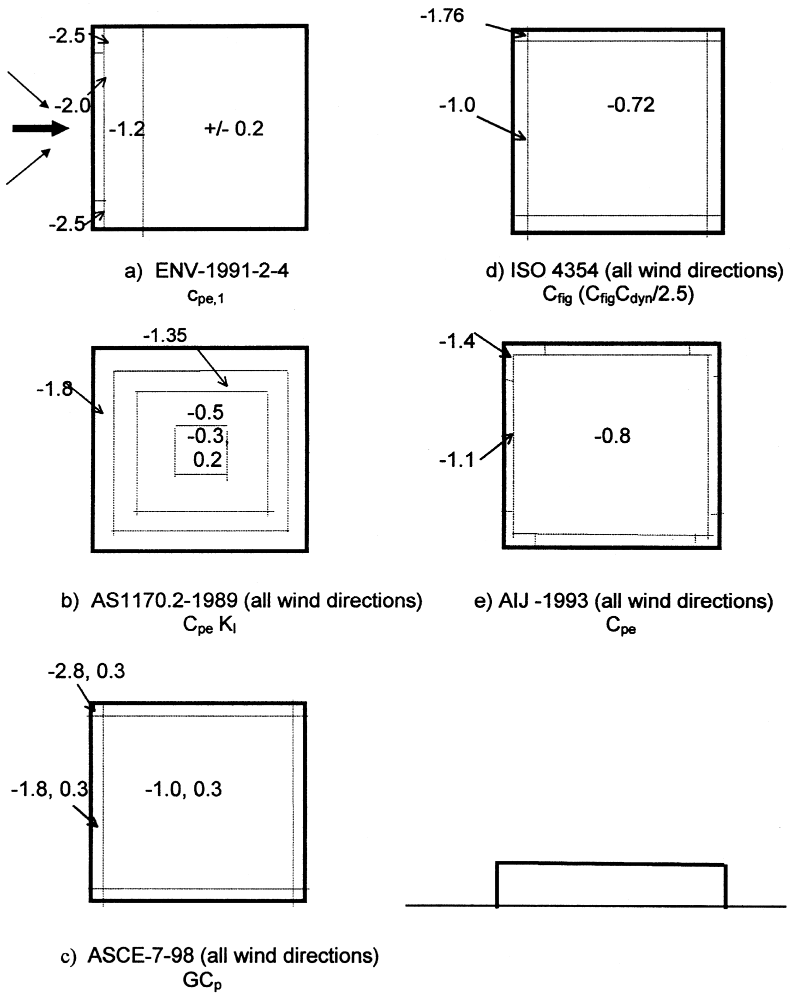

Figure 15.2 Comparison of pressure coefficients for a flat roof local cladding loads (<1 m^2) $h/d = 0.2$.

15.7.2 Case (b) Square plan canopy with flat free roof

Only three codes of the group specify pressures for canopies or free roofs – the Australian and British Standards, and the draft Eurocode. In these cases *net* pressure difference coefficients are given. Figures 15.3 and 15.4 give the pressure coefficients for structural and cladding loads, respectively. The Eurocode gives the same pressure coefficients for main structural loads and cladding and applies them over the whole roof – obviously very much a simplification. AS1170.2 specifies pressures for zones based on distance from the windward edge as for the enclosed building. In all codes upwards (negative) and downwards (positive) pressures are specified. Higher upwards net pressures are specified for cladding along the roof edges and at the corners in the Australian and British Standards

(Figure 15.4). The British Standard specifies higher positive (downwards) net pressure coefficients than negative values for local cladding loads, along the edges.

15.7.3 Case (c) Square plan enclosed building with arched roof

Figure 15.5 shows the pressure coefficients for an enclosed building with an arched roof, which is covered in all codes except the British Standard. The ISO Standard only gives loads for one geometrical shape of arched roof – this has a lower wall height and a slightly lower rise/span ratio, but is shown in Figure 15.5 for completeness. The values given in AS1170.2-1989 and ASCE-7-98 are identical to each other, as are the values in ENV-1991-2-4 and the AIJ (commentary only). The zone system in ENV-1991-2-4 and AIJ is the same as AS1170.2 and ASCE-7, but the coefficients are different. The largest magnitude negative pressure coefficients in the central part of the roof are quite similar in the five codes, being in the range –0.72 to –0.9.

15.7.4 Case (d) Circular plan enclosed building with domed roof

ENV-1991-2-4 and the AIJ are the only documents to give pressures for a domed roof – these are shown in Figure 15.6. Values at the windward and leeward points on the roof,

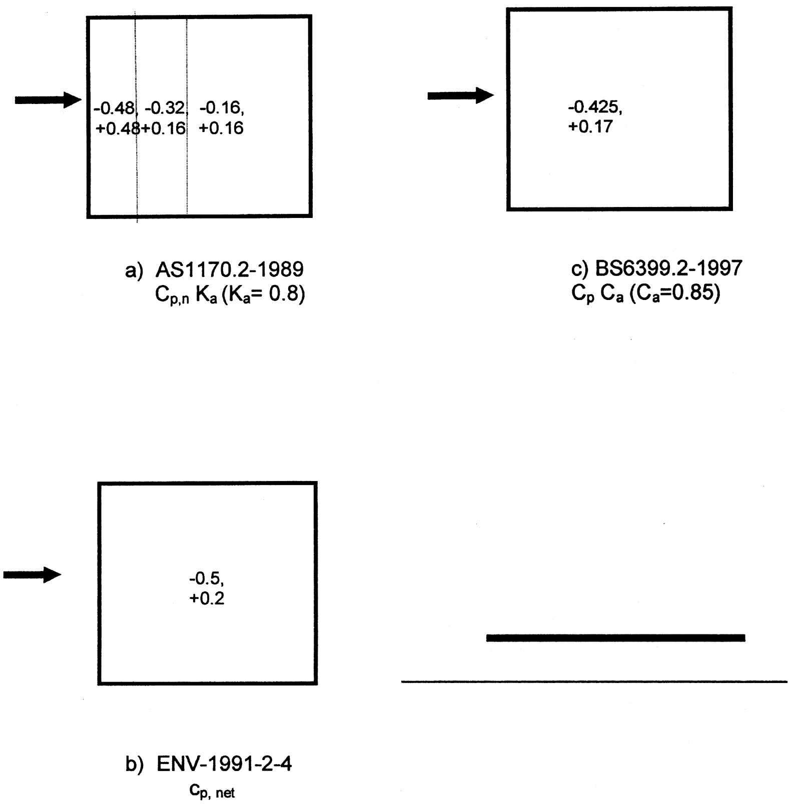

Figure 15.3 Comparison of pressure coefficients for a flat free roof (empty under – main structural loads) $h/d = 0.2$.

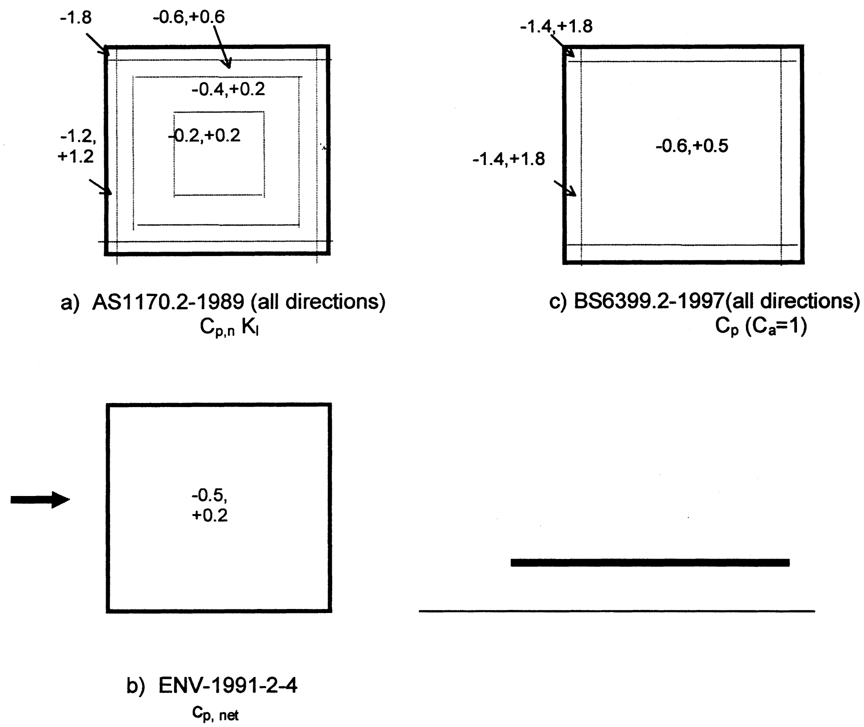

Figure 15.4 Comparison of pressure coefficients for a flat free roof (empty under – local cladding loads) $h/d = 0.2$.

and along a line perpendicular to the apex of the roof are given. Interpolation between the values shown along the arcs of circles parallel to the wind is recommended. Generally, the values are similar in magnitude to the arched roof.

15.8 Other shapes and sectional force coefficients

Apart from the AIJ Recommendations, which is intended exclusively for buildings, all the surveyed documents contain shape, or force, coefficients for a variety of structure shapes and cross-sections. Table 15.3 summarizes the data given.

The data in ISO 4354 (non-rectangular buildings) is quite old and pre-dates boundary-layer wind tunnels. The data in the other documents appears to be based on modern wind tunnel measurements for the most part. ENV 1991-2-4 clearly contains the most comprehensive set of data. As previously stated, the AIJ has the least amount of additional data.

15.9 Dynamic response calculations

The first five standards contain procedures for the calculation of dynamic response for wind-sensitive structures, such as slender, flexible, lightly damped tall buildings. Both ASCE 7-98 and AS1170.2 classify wind-sensitive structures as those with a first-mode natural frequency less than 1 Hz, and a height to breadth (or depth) ratio greater than four

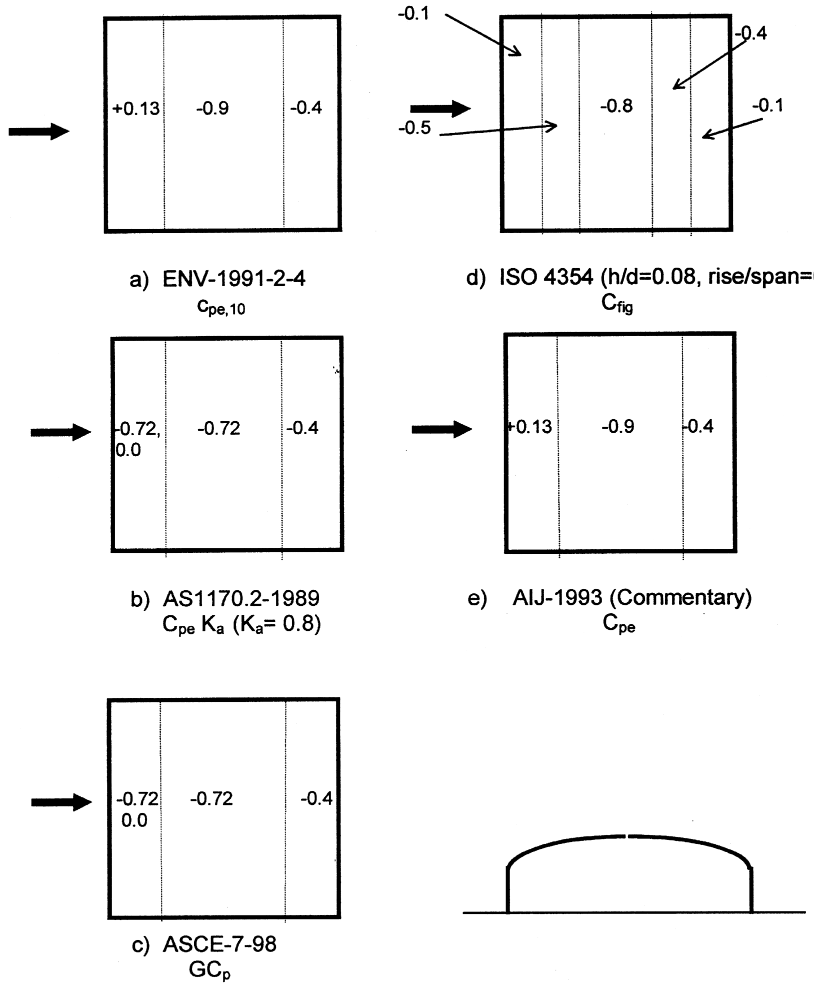

Figure 15.5 Comparison of pressure coefficients for an arched roof (main structural loads) $h/d = 0.2$, rise/span $= 0.2$.

(ASCE 7-98) or five (AS1170.2). ISO 4354 considers a structure slender if the height to diameter ratio exceeds six.

ISO 4354 recommends the use of a 'dynamic response factor' C_{dyn} to account for dynamic wind action caused by random wind gusts acting in the along-wind direction, fluctuating wind pressures induced by the wake of the structure, including vortex-shedding forces, and other fluctuating forces induced by the motion of the structure. However, the recommended procedure for the calculation of the dynamic response factor is only available for the along-wind response to gusts. In this case, the 'dynamic response factor' is defined as the ratio of the maximum load effect to the mean load effect. That is, it is actually a *gust response factor* (Section 5.3.2):

$$C_{\mathrm{dyn}} = 1 + 2g_w I_u \sqrt{(B^2 + R^2)} \qquad (15.3)$$

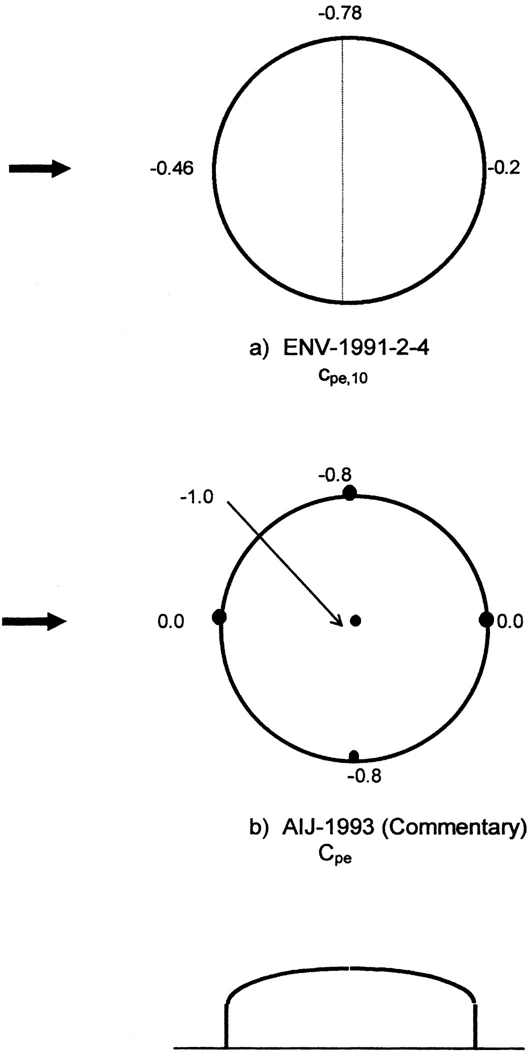

Figure 15.6 Comparison of pressure coefficients for a domed roof (main structural loads) $h/d = 0.2$, rise/span $= 0.2$.

where g_w is a peak factor, I_u is turbulence intensity, B is a background response factor (dependent on the size of the building), and R is a resonant response factor.

Representative values of structural damping ratio for typical steel and concrete structures are also given, together with a suggested acceptance criterion for habitable buildings.

Although ISO 4354 recognises the importance of vortex shedding in causing dynamic cross-wind effects in slender prismatic and cylindrical structures, only circular cylindrical structures are dealt with in detail. Strouhal numbers for circular and near-circular cylinders are given, to enable the critical wind speed at which large amplitude motions may result, to be calculated. The sign and magnitude of an equivalent aerodynamic damping is

Table 15.3 Shape factors contained in the various documents (excluding rectangular enclosed buildings)

Type	*ISO 4354*	*ENV-1991*	*ASCE 7-98*	*AIJ*	*AS1170.2*	*BS6399*
Stepped roofs	no	no	yes	no	no	yes
Free-standing walls, hoardings	yes	yes	yes	no	yes	yes
Free-standing roofs (canopies)	no	yes	no	no	yes	yes
Attached canopies	no	no	no	no	yes	yes
Multispan roofs (enclosed)	no	yes	yes	yes[a]	yes	yes
Multispan canopies	no	yes	no	no	no	no
Arched roofs	yes	yes	yes	yes[a]	yes	no
Domes	no	yes	no	yes[a]	no	no
Bins, silos, tanks	yes	yes	yes	no	yes	no
Circular sections	yes	yes	yes	yes	yes	yes
Polygonal sections	no	yes	yes	no	yes	no
Structural angle sections	yes	yes	no	no	yes	yes
Bridge decks	no	yes	no	no	no	no
Lattice sections	yes	yes	yes	no	yes	no
Flags	no	yes	no	no	no	no
Sphere	no	yes	no	no	no	no

[a] Given in commentary section of Japanese language version.

required to further assess the potential for large amplitude vortex-induced motions. Expressions for the amplitude of stable motion, and an equivalent static wind force distribution are also given.

ENV 1991-2-4 has adopted a dynamic coefficient c_d for the design of dynamically sensitive structures. Using the same notation as that in equation (15.3), but not the same as in ENV 1991-2-4, c_d can be written as:

$$c_d = \frac{1 + 2gI_u\sqrt{B^2 + R^2}}{1 + 2gI_u} \tag{15.4}$$

This form is intended for use with a *gust* dynamic pressure not a mean dynamic pressure, and is the *dynamic response factor* discussed in Section 5.3.4. Values greater than one indicate significant resonant dynamic response, R.

A comprehensive set of graphs of dynamic coefficient is given for a full range of structures, including buildings, chimneys and bridges. A detailed procedure is recommended for buildings and structures with values of dynamic coefficient in the range 1.0 to 1.2, with relevant information in Annexes B and C. Expressions for maximum along-wind displacement and standard deviation of along-wind acceleration are also given.

Comprehensive information, including working equations, regarding vortex excitation and other aeroelastic effects such as vortex-induced large amplitude lock-in type vibrations, galloping (Section 5.5.2), various types of interference excitations, flutter (Section 5.5.3) and ovalling of shell structures, are included in Annex C of ENV 1991-2-4. Recommended calculation procedures for dynamic structural properties, including natural frequencies, mode shapes, equivalent masses and logarithmic decrement are also given.

In ASCE 7-98, an analytical procedure for the determination of a 'gust effect factor', G_f, for the along-wind vibrations of flexible buildings and other structures, is presented in the commentary. The development of this factor was described by Solari and Kareem (1998). The gust effect factor is, in fact, a *dynamic response factor* (Section 5.3.4), defined in the same way as the dynamic coefficient, c_d, in ENV 1991-2-4, i.e. it is based on equation (15.4) for use with dynamic pressure based on a 3-second gust wind speed. The calculation procedure is nearly identical to that in ENV 1991-2-4, making use of the closed form equations of Solari (1983). Expressions for maximum along-wind displacement and standard deviation and maximum along-wind acceleration are also given. However, no analytical procedure for cross-wind response is given.

In the AIJ recommendations, a Detailed Procedure II is applied to estimate the dynamic response of wind-sensitive structures. For along-wind response, a standard gust response factor approach along the lines of equation (15.3) is used to determine a gust effect factor G_f. Vortex-induced cross-wind vibration and wind loads are determined, based on r.m.s. cross-wind overturning moment data obtained from wind-tunnel tests. Expressions for effective cross-wind load distributions, displacement and acceleration are given. However, the cross-wind response calculations are restricted to prismatic cross-sections with a height to breadth ratio no greater than six, and to wind directions normal to a face of the building. Expressions for torsional angular acceleration and torsional wind load distribution are also given. Guidelines for assessing potential aeroelastic instabilities including lock-in type vortex resonance and galloping instabilities are presented.

The dynamic along-wind and cross-wind responses of tall buildings and towers are dealt with in Section 4, Detailed Procedure: Dynamic Analysis, of AS1170.2. An approach based on equation (15.3) is adopted to determine a gust (response) factor, G, from which the design base overturning moment is calculated, by multiplying the mean base overturning moment by it. The methodology is a modified version of that described by Vickery (1971). To determine the mean wind pressures, a different set of terrain height multipliers is provided to convert the basic gust speed to an hourly mean wind speed.

Cross-wind base overturning moment and acceleration can be determined from cross-wind force spectrum coefficients, derived from wind tunnel test data for a series of square and rectangular section buildings, with the incident wind normal to a face. Suggested values of damping for a range of steel and concrete structures under different stress levels are given. The importance of aeroelastic instabilities, such as lock-in, galloping, flutter and interference are discussed separately in an Appendix to AS1170.2.

The British Standard, BS 6399: Part 2, contains a 'dynamic augmentation factor', C_r, which is, in fact, not applied directly as a factor, but in the form $(1 + C_r)$ to the overall horizontal loads on buildings. It is intended for application to 'mildly dynamic structures'. If the value of C_r obtained from the graph in BS6399 exceeds 0.25, or if the height of the structure exceeds 300 m, the user is referred to other codes, and other references, for further information.

15.10 Future developments

This chapter has reviewed the provisions of six major and current (at the time of writing) standards for wind loading. Considerable differences exist in both format and the type of information presented in these documents.

At the time of writing, the Australian Standard (AS1170.2) is under revision as a combined document with the wind loading rules for New Zealand. Although there is considerable change in the format (with alignment with ISO 4354), the basic calculation method for static structures will remain the same. There has been a re-analysis of wind speeds for the regions not affected by tropical cyclones, and the directional multiplier system will be extended. There will be some freedom in choice of the return period by the designer. There will also be differences in the dynamic analysis method, which will be based on a 'dynamic response factor' approach based on gust wind speeds (Section 5.3.4), rather than the 'gust response factor' approach, based on mean wind speeds (Section 5.3.2).

At present, there is no generally used international standard on wind loading, although eventually the final version of Eurocode 1 will be adopted in most of Europe. At the time of writing there are moves to redraft the International standard, ISO 4354, into a form that is widely acceptable, and usable by structural engineers. Hopefully then national and regional standards will gradually be amended to be of similar form. The first requirement is a common format and notation. For wide international acceptance in tropical and sub-tropical, as well as temperate climates, the special requirements of regions affected by typhoons (tropical cyclones or hurricanes) and thunderstorms, will need to be incorporated.

References

American Society of Civil Engineers (1998) 'Minimum design loads for buildings and other structures', ANSI/ASCE 7-98, A.S.C.E., New York.

Architectural Institute of Japan (1996) 'AIJ recommendations for loads on buildings', English translation, AIJ, Tokyo.

British Standards Institution (1997) *Loading for Buildings. Part 2. Code of Practice for Wind Loads*. BS 6399: Part 2: 1997.

C.E.N. (European Committee for Standardization). (1994) 'Eurocode 1: basis of design and actions on structures. Part 2-4: Wind actions', ENV-1991-2-4, C.E.N., Brussels.

Cook, N. J. (1990) *The Designer's Guide to Wind Loading of Building Structures. Part 2 Static Structures*. London: Building Research Establishment and Butterworths.

Dorman, C. M. L. (1983) 'Extreme wind speeds in Australia, excluding tropical cyclones', *Civil Engineering Transactions, Institution of Engineers, Australia* CE25: 96–106.

—— (1984) 'Tropical cyclone wind speeds in Australia', *Civil Engineering Transactions, Institution of Engineers, Australia* CE26: 132–9.

International Standards Organization (1997) 'Wind actions on structures', ISO International Standard. ISO 4354.

Holmes, J. D. (1985) 'Wind loads and limit states design', *Civil Engineering Transactions, Institution of Engineers, Australia* CE27: 21–6.

Holmes, J. D., Melbourne W. H. and Walker G. R. (1990) *A Commentary on the Australian Standard for Wind Loads*. Australian Wind Engineering Society.

Kasperski, M. (1993) 'Aerodynamics of low-rise buildings and codification', *Journal of Wind Engineering and Industrial Aerodynamics* 50: 253–63.

Kijewski, T. and Kareem, A. (1998) 'Dynamic wind effects: a comparative study of provisions in codes and standards with wind tunnel data', *Wind and Structures* 1: 77–109.

Mehta, K. C. (1998) 'Wind load standards', *Proceedings, Jubileum Conference on Wind Effects on Buildings and Structures*, Porto Alegre, Brazil, May 25–29.

Peterka, J. A. and Shahid, S. (1998) 'Design gust wind speeds in the United States', *Journal of Structural Engineering (ASCE)* 124: 207–14.

Solari, G. (1983) 'Gust buffeting II: dynamic along-wind response', *J Struct Eng, ASCE* 119.

Solari, G. and Kareem, A. (1998) 'On the formulation of ASCE–7–95 gust effect factor', *Journal of Wind Engineering and Industrial Aerodynamics* 77–78: 673–84.

Tamura, Y., Kawai, H., Uematsu, Y., Marukawa, H., Fujii, K. and Taniike, Y. (1996) 'Wind load and wind-induced response estimations in the recommendations for loads on buildings, AIJ, 1993', *Engineering Structures* 18: 399–411.

Vickery, B. J. (1971) 'On the reliability of gust loading factors', *Civil Engineering Transactions, Institution of Engineers, Australia* CE13: 1–9.

Standards Association of New Zealand. *Code of Practice for General Structural Design and Design Loadings for Buildings*. NZS 4203: 1992.

Standards Australia (1989) *Minimum Design Loads on Structures. Part 2: Wind Loads*. Standards Australia, North Sydney, Australian Standard AS1170.2-1989.