CHAPTER 6 WIND LOADS

Outline

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Each wind load is determined by a probabilistic-statistical method based on the concept of “equivalent static wind load”, on the assumption that structural frames and components/cladding behave elastically in strong wind.

Usually, mean wind force based on the mean wind speed and fluctuating wind force based on a fluctuating flow field act on a building. The effect of fluctuating wind force on a building or part thereof depends not only on the characteristics of fluctuating wind force but also on the size and vibration characteristics of the building or part thereof. These recommendations evaluate the maximum loading effect on a building due to fluctuating wind force by a probabilistic-statistical method, and calculate the static wind load that gives the equivalent effect. The design wind load can be obtained from the summation of this equivalent static wind load and the mean wind load.

A suitable wind load calculation method corresponding to the scale, shape, and vibration characteristics of the design object is provided here. Wind load is classified into horizontal wind load for structural frames, roof wind load for structural frames and wind load for components/cladding. The wind load for structural frames is calculated from the product of velocity pressure, gust effect factor and projected area. Furthermore, a calculation method for horizontal wind load for lattice structural frames that stand upright from the ground is newly added. The wind load for components/cladding is calculated from the product of velocity pressure, peak wind force coefficient and subject area. For small-scale buildings, a simplified procedure can be applied.

These recommendations introduce the wind directionality factor for calculating the design wind speed for each individual wind direction, thus enabling rational design considering the building’s orientation with respect to wind direction. Moreover, the topography factor for turbulence intensity is newly added to take into account the increase of fluctuating wind load due to the increase of fluctuating wind speed.

Introduction of the wind directionality factor requires the combination of wind loads in along-wind, across-wind and torsional directions. Hence, it is decided to adopt the regulation for the combination of wind loads in across-wind and along-wind directions, or in torsional and along-wind directions explicitly. Furthermore, a prediction formula for the response acceleration of the building for evaluating its habitability to vibration, which is needed in performance design, and information of 1-year-recurrence wind speed are newly added. Besides, information has been provided for the dispersion of wind load.

Notation

Notations used in the main text of this chapter are shown here.

Uppercase Letter

A (m^2): projected area at height Z

A_R (m^2): subject area

A_C (m^2): subject area of components/cladding

A_0 (m^2): whole plane area of one face of lattice structure

A_F (m^2): projected area of one face of lattice structure

B (m): building breadth

B_1 (m): building length in span direction

B_2 (m): building length in ridge direction

B_0, B_H (m): width of lattice structure in ground and width at height H

B_D (m): background excitation factor for lattice structure

C_1, C_2, C_3 : parameters determining topography factor E_g and E_I

C_D, C_R, C_X, C_Y : wind force coefficients

C_L', C_T' : rms overturning moment coefficient and rms torsional moment

C_e : exposure factor, which is generally 1.0 and shall be 1.4 for open terrain with few obstructions (Category II). When wind speed is expected to increase due to local topography, this factor shall be increased accordingly.

C_g : overturning moment coefficient in along-wind direction

C_g' : rms overturning moment coefficient in along-wind direction

C_f : wind force coefficient. For horizontal wind loads, wind force coefficient C_D defined in A6.2 with $k_Z = 0.9$ shall be used. For roof wind loads, wind force coefficient C_R defined in A6.2 shall be used.

C_{pe} : external pressure coefficient

C_{pe1}, C_{pe2} : external pressure coefficients on windward wall and leeward wall

C_{pi} : internal pressure coefficient

C_{pi}^* : factor for effect of fluctuating internal pressure

C_r : wind force coefficient at resonance

$\hat{C}_C$: peak wind force coefficient

$\hat{C}_{pe}$: peak external pressure coefficient

D (m): building depth, building diameter, member diameter

D_B (m): building diameter at the base

D_m (m): building diameter at height of $2H/3$

E : wind speed profile factor

E_H : wind speed profile factor at reference height H

E_{I} : topography factor for turbulence intensity

E_{g} : topography factor for wind speed

E_{gI} : topography factor for turbulence intensity

E_{r} : exposure factor for flat terrain categories

F_{D} : along-wind force spectrum factor

F : wind force spectrum factor

G_{D} : gust effect factor for along-wind load

G_{R} : gust effect factor for roof wind load

H (m): reference height

H_{S} (m): height of topography

I_{T} (kgm^2): generalized inertial moment of building for torsional vibration

I_{Z} : turbulence intensity at height Z

I_{rZ} : turbulence intensity at height Z on flat terrain categories

K_{D} : wind directionality factor

L (m): span of roof beam

L_{S} (m): horizontal distance from topography top to point where height is half topography height

L_{Z} (m): turbulence scale at height Z

M (kg): total building mass

M_{D} (kg): generalized mass of building for along-wind vibration

M_{L} (kg): generalized mass of building for across-wind vibration

R : factor expressing correlation of wind pressure of windward side and leeward side

R_{D} : resonance factor for along-wind vibration

R_{L} : resonance factor for across-wind vibration

R_{T} : resonance factor for torsional vibration

R_{Re} : resonance factor for roof beam

S_{D} : size effect factor

U_0 (m/s): basic wind speed

U_1 (m/s): 1-year-recurrence 10-minute mean wind speed at 10m above ground over flat and open terrain

U_{1H} (m/s): 1-year-recurrence wind speed

U_{500} (m/s): 500-year-recurrence 10-minute mean wind speed at 10m above ground over flat and open terrain

U_{H} (m/s): design wind speed

$U^*_{\mathrm{Lcr}}, U^*_{\mathrm{Tcr}}$: non-dimensional critical wind speed for aeroelastic instability in across-wind and torsional directions

U_{r} (m/s): resonance wind speed

U^*_{T} : non-dimensional wind speed for calculating torsional wind load

U_r^* : non-dimensional resonance wind speed

W_D (N): along-wind load at height Z

W_L (N): across-wind load at height Z

W_R (N): roof wind load

W_T (Nm): torsional wind load at height Z

W_{LC} (N): across-wind combination load

W_{SC} (N): wind load on components/cladding obtained by simplified method

W_{SF} (N): wind load on structural frames

W_r (N): wind load at height Z

X_S (m): distance from leading edge of topography to construction site

Z (m): height above ground

Z_b , Z_G (m): parameters determining exposure factor

Lowercase Letter

a_{Dmax} , a_{Lmax} (m/s^2), a_{Tmax} (rad/s^2): maximum response acceleration in along-wind, across-wind and torsional directions at top of building

b (m): projected width of member

f (m): rise

f_1 (Hz): The smaller of f_L and f_T

f_D , f_L , f_T (Hz): natural frequency for first mode in along-wind, across-wind and torsional directions

f_R (Hz): natural frequency for first mode of roof beam

g_{aD} , g_{aL} , g_{aT} : peak factors for response accelerations in along-wind, across-wind and torsional directions

g_D , g_L , g_T : peak factors for wind loads in along-wind, across-wind and torsional directions

h (m): eaves height

k_1 : factor for aspect ratio

k_2 : factor for surface roughness

k_3 : factor for end effects

k_C : area reduction factor

k_{rW} : return period conversion factor

k_Z : factor for vertical profile for wind pressure coefficients or wind force coefficients

l (m): smaller value of $4H$ and B , minimum value of $4H$, B_1 and B_2 , member length

l_{a1} (m): smaller value of H and B_1

l_{a2} (m): smaller value of H and B_2

q_H (N/m^2): velocity pressure at reference height H

q_Z (N/m^2): velocity pressure at height Z

r (year): design return period

r_{Re} : coefficient of variation for generalized external pressure

x (m) : distance from end of component

Greek Alphabet

α : exponent of power law for wind speed profile

β : exponent of power law for vibration mode

γ : load combination factor

$\delta_{\mathrm{D}}, \delta_{\mathrm{L}}, \delta_{\mathrm{T}}$: mass damping parameter

$\phi_{\mathrm{D}}, \phi_{\mathrm{L}}, \phi_{\mathrm{T}}$: mode correction factor

$\zeta_{\mathrm{D}}, \zeta_{\mathrm{L}}, \zeta_{\mathrm{T}}$: critical damping ratio for first translational and torsional modes

ζ_{R} : critical damping ratio for first mode of roof beam

φ : solidity

λ : mode correction factor of general wind force

λ_{U} : U_{500} / U_0

μ : first mode shape in each direction

ν_{D} (Hz): level crossing factor

θ (°): roof angle, angle of attack to member

θ_{S} (°): inclination of topography

ρ (kg/m^3): air density

ρ_{S} (kg/m^3): building density which is $M/(HD_{\mathrm{m}}D_{\mathrm{B}})$

ρ_{LT} : correlation coefficient between across-wind vibration and torsional vibration

6.1 General

6.1.1 Scope of application

(1) Target strong wind

Most wind damage to buildings occurs during strong winds. The wind loads specified here are applied to the design of buildings to prevent failure due to strong wind. The strong winds that occur in this country are mainly those that accompany a tropical or extratropical cyclone, and down-bursts or tornados. The former are large-scale phenomena that are spread over about 1000km in a horizontal plane, and their nature is comparatively well known. Down-bursts are gusts due to descending air flows caused by severe rainfall in developed cumulonimbus. Since the scale of these phenomena are very small, few are picked up by the meteorological observation network. It is known that tornados are small-scale phenomena several hundred meters wide at most having a rotational wind with a rapid atmospheric pressure descent. The characteristics of the strong wind and pressure fluctuation caused by tornados are not known. The number of occurrences of down-bursts and tornados is relatively large, but their probability of attacking a particular site is very small compared with that of the tropical or extratropical cyclones. However, the winds caused by down-bursts and tornados are very strong, so they often fatally damage buildings. These recommendations focus on strong winds caused by tropical or extratropical cyclones. However, the minimum wind speed takes into account the influence of tornadoes and down-bursts.

(2) Wind loads on structural frames and wind loads on components/cladding

The wind loads provided in these recommendations is composed of those for structural frames and those for components/cladding. The former are for the design of structural frames such as columns and beams. The latter are for the design of finishings and bedding members of components/cladding and their joints. Wind loads on structural frames and on components/cladding are different, because there are large differences in their sizes, dynamic characteristics and dominant phenomena and behaviors. Wind loads on structural frames are calculated on the basis of the elastic response of the whole building against fluctuating wind forces. Wind loads on components/cladding are calculated on the basis of fluctuating wind forces acting on a small part.

Wind resistant design for components/cladding has been inadequate until now. They play an important role in protecting the interior space from destruction by strong wind. Therefore, wind resistant design for components/cladding should be just as careful as that for structural frames.

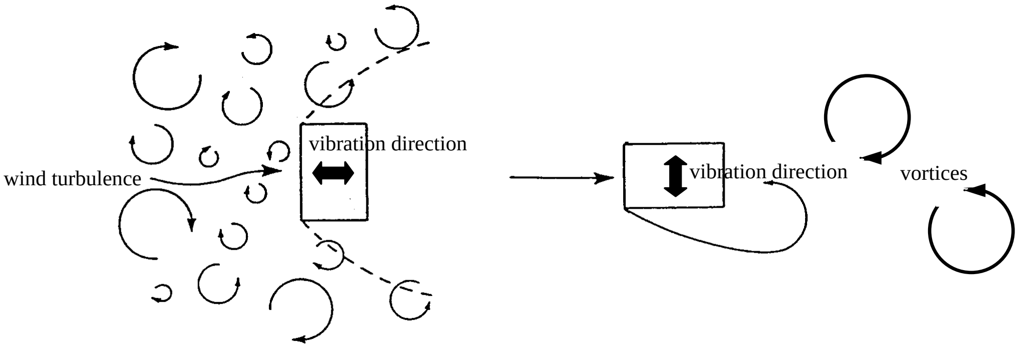
6.1.2 Estimation principle

(1) Classification of wind load

A mean wind force acts on a building. This mean wind force is derived from the mean wind speed and the fluctuating wind force produced by the fluctuating flow field. The effect of the fluctuating wind force on the building or part thereof depends not only on the characteristics of the fluctuating wind force but also on the size and vibration characteristics of the building or part thereof. Therefore, in order to estimate the design wind load, it is necessary to evaluate the characteristics of fluctuating wind forces and the dynamic characteristics of the building.

The following factors are generally considered in determining the fluctuating wind force.

1) wind turbulence (temporal and spatial fluctuation of wind)
2) vortex generation in wake of building
3) interaction between building vibration and surrounding air flow



a) fluctuating wind force caused by
wind turbulence

b) fluctuating wind force caused by
vortex generation in wake of building

Figure 6.1.1 Fluctuating wind forces based on wind turbulence and vortex generation in wake of building

Fluctuating wind pressures act on building surfaces due to the above factors. Fluctuating wind pressures change temporally, and their dynamic characteristics are not uniform at all positions on the building surface. Therefore, it is better to evaluate wind load on structural frames based on overall building behavior and that on components/cladding based on the behavior of individual building parts. For most buildings, the effect of fluctuating wind force generated by wind turbulence is predominant. In this case, horizontal wind load on structural frames in the along-wind direction is important. However, for relatively flexible buildings with a large aspect ratio, horizontal wind loads on structural frames in the across-wind and torsional directions should not be ignored. For roof loads, the fluctuating wind force caused by separation flow from the leading edge of the roof often predominates. Therefore, wind load on structural frames is divided into two parts: horizontal wind load on structural frames and roof wind load on structural frames.

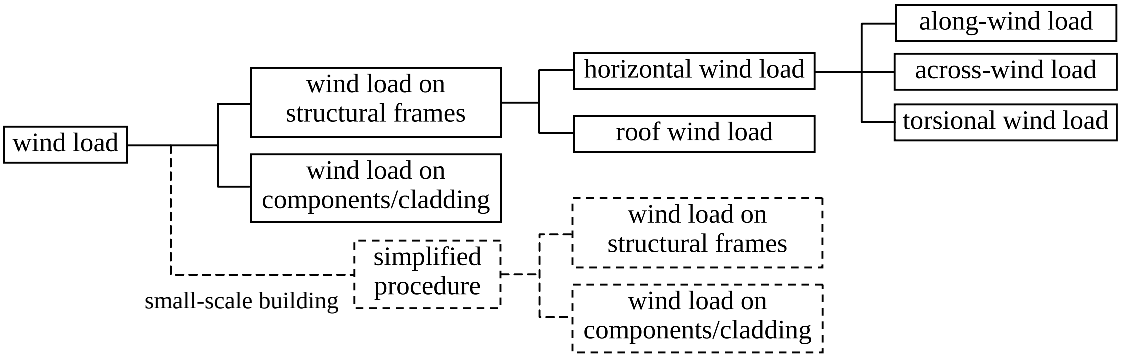


Figure 6.1.2 Classification of wind loads

(2) Combination of wind loads

Wind pressure distributions on the surface of a building with a rectangular section are asymmetric even when wind blows normal to the building surface. Therefore, wind forces in the across-wind and torsional directions are not zero when the wind force in the along-wind direction is a maximum.

Combination of wind loads in the along-wind, across-wind and torsional directions have not been taken into consideration positively so far, because the design wind speed has been used without considering the effect of wind direction. However, with the introduction of wind directionality, combination of wind loads in the along-wind, across-wind and torsional directions has become necessary. Hence, it has been decided to adopt explicitly a regulation for combination of wind loads in along-wind, across-wind and torsional directions.

(3) Wind directionality factor

Occurrence and intensity of wind speed at a construction site vary for each wind direction with geographic location and large-scale topographic effects. Furthermore, the characteristics of wind forces acting on a building vary for each wind direction. Therefore, rational wind resistant design can be applied by investigating the characteristics of wind speed at a construction site and wind forces acting on the building for each wind direction. These recommendations introduce the wind directionality factor in calculating the design wind speed for each wind direction individually. In evaluating the wind directionality factor, the influence of typhoons, which is the main factor of strong winds in Japan, should be taken into account. However, it was difficult to quantify the probability distribution of wind speed due to a typhoon from meteorological observation records over only about 70 years, because the occurrence of typhoons hitting a particular point is not necessarily high. In these recommendations, the wind directionality factor was determined by conducting Monte Carlo simulation of typhoons, and analysis of observation data provided by the Metrological Agency.

(4) Reference height and velocity pressure

The reference height is generally the mean roof height of the building, as shown in Fig.6.1.3. The wind loads are calculated from the velocity pressure at this reference height. The vertical distribution of wind load is reflected in the wind force coefficients and wind pressure coefficients. However, the wind load for a lattice type structure shall be calculated from the velocity pressure at each height, as shown in Fig.6.1.3.

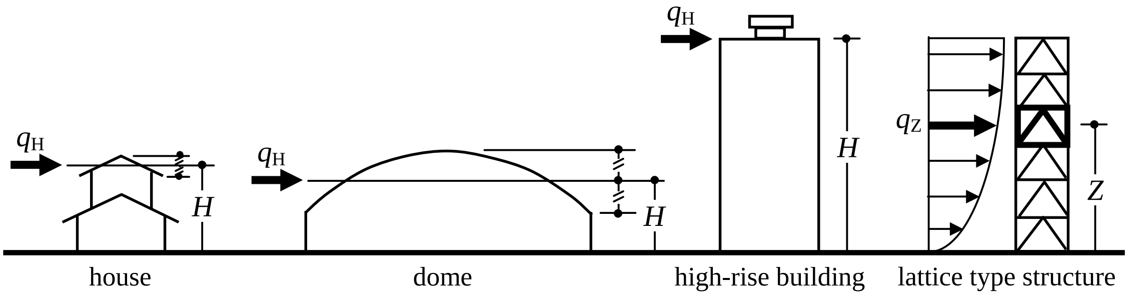


Figure 6.1.3 Definition of reference height and velocity pressure

(5) Wind load on structural frames

The maximum loading effect on each part of the building can be estimated by the dynamic response analysis considering the characteristics of temporal and spatial fluctuating wind pressure and the dynamic characteristics of the building. The equivalent static wind load producing the maximum loading effect is given as the design wind load. For the response of the building against strong wind, the first mode is predominant and higher frequency modes are not predominant for most buildings. The horizontal wind load (along-wind load) distribution for structural frames is assumed to be equal to the mean wind load distribution, because the first mode shape resembles the mean building displacement. Specifically, the equivalent wind load is obtained by multiplying the gust effect factor, which is defined as the ratio of the instantaneous value to the mean value of the building response, to the mean wind load. The characteristics of the wind force acting on the roof are influenced by the features of the fluctuating wind force caused by separation flow from the leading edge of the roof and the inner pressure, which depends on the degree of sealing of the building. Therefore, the characteristics of roof wind load on structural frames are different from those of the along-wind load on structural frames. Thus, the roof wind load on structural frames cannot be evaluated by the same procedure as for the along-wind load on structural frames. Here, the gust effect factor is given when the first mode is predominant and assuming elastic dynamic behavior of the roof beam under wind load.

(6) Wind load on components/cladding

In the calculation of wind load on components/cladding, the peak exterior wind pressure coefficient and the coefficient of inner wind pressure variation effect are prescribed, and the peak wind force coefficient is calculated as their difference. Only the size effect is considered. The resonance effect is ignored, because the natural frequency of components/cladding is generally high. The wind load on components/cladding is prescribed as the maximum of positive pressure and negative pressure for each part of the components/cladding for wind from every direction, while the wind load on structural frames is prescribed for the wind direction normal to the building face. Therefore, for the wind load on components/cladding, the peak wind force coefficient or the peak exterior wind pressure coefficient must be obtained from wind tunnel tests or another verification method.

(7) Wind loads in across-wind and torsional directions

It is difficult to predict responses in the across-wind and torsional directions theoretically like along-wind responses. However, a prediction formula is given in these recommendations based on the fluctuating overturning moment in the across-wind direction and the fluctuating torsional moment for the first vibration mode in each direction.

(8) Vortex induced vibration and aeroelastic instability

Vortex-induced vibration and aeroelastic instability can occur with flexible buildings or structural members with very large aspect ratios. Criteria for across-wind and torsional vibrations are provided for buildings with rectangular sections. Criteria for vortex-induced vibrations are provided for buildings and structural members with circular sections. If these criteria indicate that vortex-induced vibration or aeroelastic instability will occur, structural safety should be confirmed by wind tunnel tests and so on. A formula for wind load caused by vortex-induced vibrations is also provided for buildings or structural members with circular sections.

(9) Small-scale buildings

For small buildings with large stiffness, the size effect is small and the dynamic effect can be neglected. Thus, a simplified procedure is employed.

(10) Effect of neighboring buildings

When groups of two or more tall buildings are constructed in proximity to each other, the wind flow through the group may be significantly deformed and cause a much more complex effect than is usually acknowledged, resulting in higher dynamic pressures and motions, especially on neighboring downstream buildings.

(11) Assessment of building habitability

Building habitability against wind-induced vibration is usually evaluated on the basis of the maximum response acceleration for 1-year-recurrence wind speed. Hence, these recommendations show a map of 1-year-recurrence wind speed based on the daily maximum wind speed observed at meteorological stations and a calculation method for response acceleration.

(12) Shielding effect by surrounding topography or buildings

When there are topographical features and buildings around the construction site, wind loads or wind-induced vibrations are sometimes decreased by their shielding effect. Rational wind resistant design that considers this shielding effect can be performed. However, changes to these features during the building’s service life need to be confirmed. Furthermore, the shielding effect should be investigated by careful wind tunnel study or other suitable verification methods, because it is generally complicate and cannot be easily analyzed.

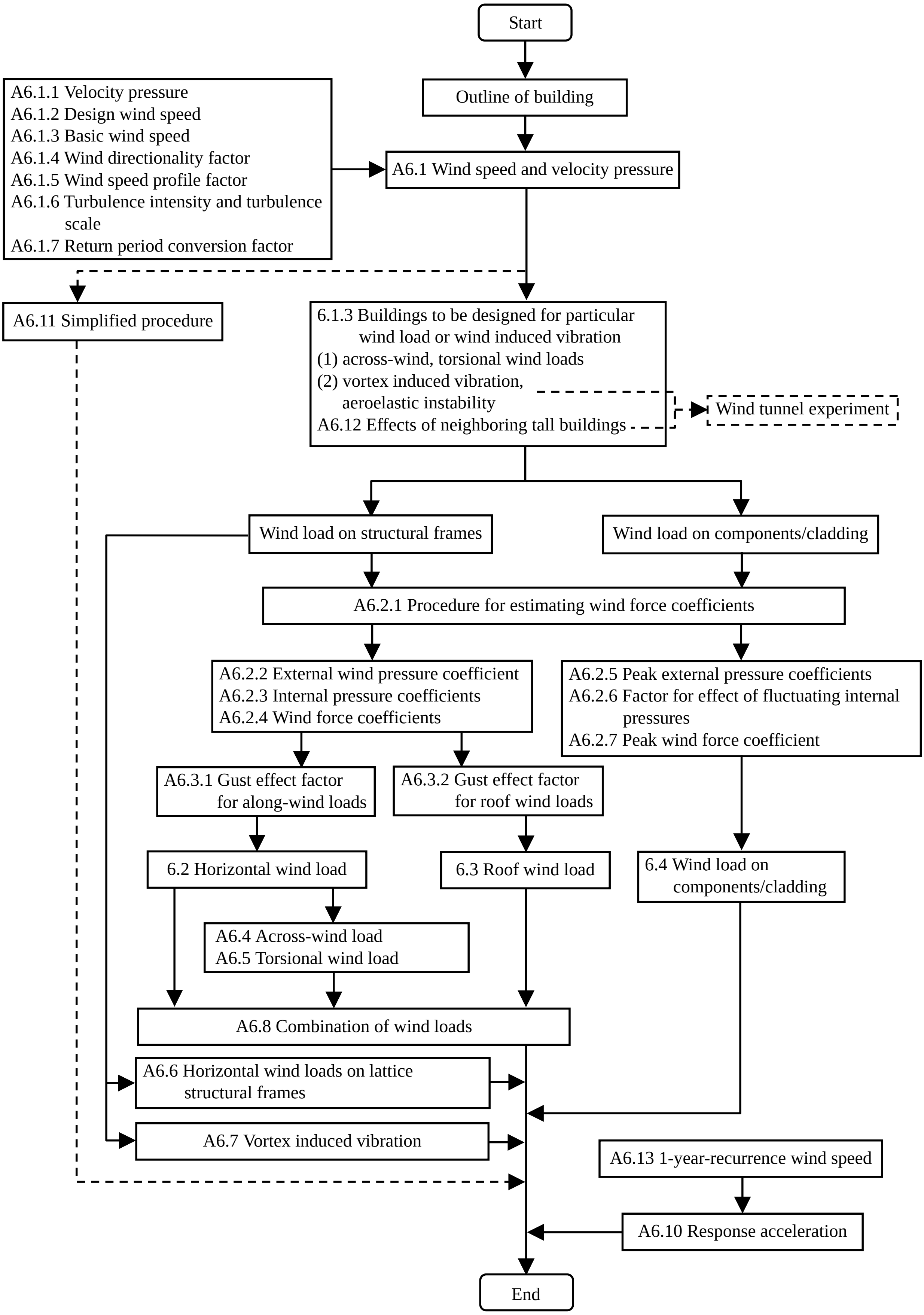


Figure 6.1.4 Flow for estimation of wind load

6.1.3 Buildings for which particular wind load or wind induced vibration need to be taken into account

(1) Buildings for which horizontal wind loads on structural frames in across-wind and torsional directions need to be taken into account

Horizontal wind loads on structural frames imply along-wind load, across-wind load and torsional wind load. Both across-wind load and torsional wind load must be estimated for wind-sensitive buildings that satisfy Eq.(6.1). Figure 6.1.5 shows the definition of wind direction, 3 component wind loads and building shape.

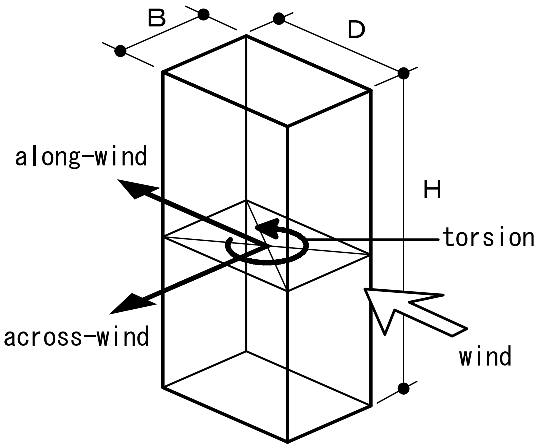


Figure 6.1.5 Definition of load and wind direction

Both across-wind vibration and torsional vibration are caused mainly by vortices generated in the building's wake. These vibrations are not so great for low-rise buildings. However, with an increase in the aspect ratio caused by the presence of high-rise buildings, a vortex with a strong period uniformly generated in the vertical direction, and across-wind and torsional wind forces increase. However, with increase in building height, the natural frequency decreases and approaches the vortex shedding frequency. As a result, resonance components increase and building responses become large. In general, responses to across-wind vibration and torsional vibration depending on wind speed increase more rapidly than responses to along-wind vibration. Under normal conditions, along-wind responses to low wind speed are larger than across-wind responses. However, across-wind responses to high wind speed are larger than along-wind responses. The wind speed at which the degrees of along-wind response and across-wind response change places with each other differs depending on the height, shape and vibration characteristics of the building. The condition with regard to the aspect ratio of Eq.(6.1) has been established through investigation of the relationship between the magnitude of along-wind loads and across-wind loads for flat terrain subcategory II and a basic wind speed of 40m/s assuming 180kg/m^3 building density, $f_1 = 1/(0.024H)$ (Hz) natural frequency of the primary mode and 1% damping ratio for an ordinary building. Therefore, it is desirable to estimate across-wind and torsional wind loads even for buildings of light weight and small damping to which Eq.(6.1) is not applicable.

Furthermore, for flat-plane buildings with small torsional stiffness or buildings with large eccentricity whose translational natural frequency and torsional natural frequency approximate each other, it is also desirable to estimate the torsional wind loads even where Eq.(6.1) is not applicable to those buildings.

The discriminating conditional formula shown in this chapter was derived for a building with a rectangular plane. It is possible to apply Eq.(6.1) to a building with a plane that is slightly different from rectangular by regarding B and D roughly as projected breadth and a depth. For values of B and D changed in the vertical direction, the wind force acting on the upper part has a major effect on the response. Therefore, a representative value for the upper part should used for the computation. Under normal conditions, a value in the vicinity of 2/3 of the building height is chosen in most cases. The computation of Eq.(6.1) using a smaller value for the upper part yields a conservative value.

(2) Vortex resonance and aeroelastic instability

It is feared that aeroelastic instabilities such as vortex-induced vibration, galloping and flutter occur in buildings with low natural frequency and are high in comparison with their breadth and depth, as well as in slender members. The conditions for estimation of aeroelastic instability in both across-wind vibration and torsional vibration for building with rectangular planes as well as the conditions for estimation of vortex-induced vibrations for a building with a circular plane are given based on wind tunnel test results and the field measurement results [1)-6)]. The method for estimating the wind load for a building with a circular plan when vortex-induced vibration occurs is shown in A6.7. It may well be that vortex-induced vibration and aeroelastic instability will occur in a slender building with a triangular or an elliptical plan. Therefore, attention must be paid to this.

The first condition required for estimating aeroelastic instability and vortex-induced vibration is the aspect ratio ($H/\sqrt{BD}$ or H/D_{m}). Aeroelastic instability as well as vortex-induced vibration does not occur easily in buildings with a small aspect ratio. Under this recommendation, the aspect ratio for estimating both aeroelastic instability and vortex-induced vibration was set to 4 or more and 7 or more, respectively. The second condition for estimating non-dimensional wind speed is ($U/f\sqrt{BD}$ or U/fD_{m}). The occurrence of aeroelastic instability and vortex-induced vibration is dominated by the non-dimensional wind speed, which is determined by the representative breadth of the building, its natural frequency and wind speed. The non-dimensional critical wind speed for aeroelastic instability depends upon the mass damping parameter, which is determined by the side ratio, the turbulence characteristics of an approaching flow and the mass and damping ratio of a building. Thus, the non-dimensional critical wind speed with regard to the estimation of aeroelastic instability of a building with a rectangular plane was provided as the function for those parameters. The non-dimensional wind speed for vortex-induced vibration of a building with a circular plan is almost independent of this parameter. Therefore, the value for non-dimensional critical wind speed is fixed. The non-dimensional wind speed for estimating aeroelastic instability and vortex-induced vibration is set at 0.83(=1/1.2) times the non-dimensional critical wind speed. This is because it is known that aeroelastic instability or vortex-induced vibration occurs within a period shorter than 10 min, which is the evaluation time for wind speed prescribed in this recommendation, and that the uncertainty of the non-dimensional wind speed including errors in experimental values is taken into account.

Furthermore, the damping ratio of a building is required for the computation of the building's mass damping parameter. It is thus recommended that the damping ratio of a building be estimated through reference to "Damping in Buildings" 7).

6.2 Horizontal Wind Loads on Structural Frames

6.2.1 Scope of application

This section describes horizontal wind loads on structural frames in the along-wind direction. The along-wind load is generally composed of a mean component caused by the mean wind speed, a quasi-static component caused by relatively low frequency fluctuation and a resonant component caused by fluctuation in the vicinity of the natural frequency. For many buildings, only the first mode is taken into account as the resonant component. The procedure described in this section can estimate the equivalent static wind load producing the maximum structural responses (load effects of stress and displacement) using the gust effect factor. The equivalent static wind load is also divided into the mean component, quasi-static component and resonant component. Although the vertical profiles for these components are different from each other, it is assumed that all profiles similar to that of the mean component are provided.

6.2.2 Estimation method

Equation (6.4) for horizontal wind loads is derived from a gust effect factor method, which includes the effect of along-wind dynamic response due to atmospheric turbulence of approaching wind. The gust effect factor is a magnifying rate of the maximum instantaneous value to the mean building responses. Davenport, who first proposed the gust effect factor, calculated this factor based on the displacement at the highest position of a building8). However, in these recommendations the gust effect factor based on the overturning moment of a base,9) which can rationally estimate the design wind load for a building, was employed. Projected area A is the area projected from the wind direction for the portion concerned, as shown in Fig.6.2.1, and for wind load at a unit height being taken into account, projected area A becomes projected breadth B.

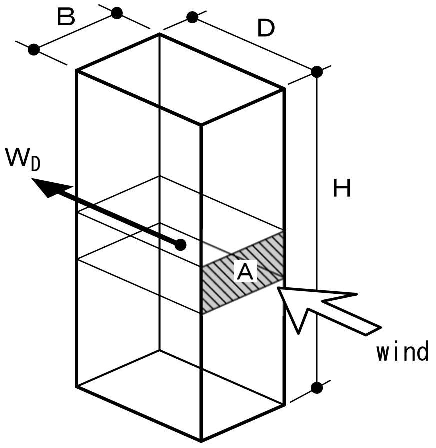


Figure 6.2.1 Projected area

6.3 Roof Wind Load on Structural Frames

6.3.1 Scope of application

Roof wind loads on structural frames should be estimated from load effects of wind forces that act on roof frames. The properties of wind forces acting on roofs are influenced by the external pressures, which are affected by the behavior of the separated shear layers from leading edges, and the internal pressures, which are affected by the building's permeability. This section describes equations to be applied to roof frames of buildings with rectangular plan without dominant openings, where the correlation between fluctuating external pressures and fluctuating internal pressures can be ignored.

A light roof like a hanging roof might generate aerodynamically unstable oscillations. These oscillations may be generated in roof frames that satisfy the conditions of $m/\rho L < 3$, $U_H / f_{R1} L > 1$ and $I_H < 0.15$, where m is mass per unit area, ρ is air density, L is span length, U_H is design wind speed, f_{R1} is frequency of first unsymmetrical vibration mode and I_H is turbulence intensity at reference height[10),11)]. In addition, note that large amplitude vibration may occur on large-span roofs with light weight because the deflection or oscillation-induced wind force due to mean wind pressure seems to make the stiffness weak. In these cases, wind tunnel tests must be carried out to ensure that aerodynamic instability such as self-excited oscillation does not occur within the design wind speed.

6.3.2 Procedure for estimating wind loads

The equivalent static wind loads on roofs can be estimated by the gust effect factor method, which includes the effects of fluctuating external pressures and fluctuating internal pressures for roof responses. The gust effect factor is only formulated under the condition where beam oscillation is dominated by the fundamental mode. The equivalent static wind load distribution that produces the maximum load effect on a roof is not strictly similar to the mean wind pressure distribution. However, to simplify the procedure, the wind load can be estimated by multiplying the gust effect factor by the mean wind force distribution.

6.4 Wind Loads for Components/Cladding

6.4.1 Scope of application

Wind loads on components/cladding need to be designed for parts of buildings; finishings of roofs and external walls; bed members such as purlins, furring strips and studs; roof braces; and tie beams subject to strong effects of intensive wind pressure. These wind loads are also applied to the design of eaves and canopies.

6.4.2 Procedure for estimating wind loads

Wind loads on components/cladding are derived from the difference between the wind pressures acting on the external and internal faces of a building, and are calculated from Eq.(6.6). Peak wind force coefficients $\hat{C}_{\mathrm{C}}$ corresponding to the peak values of fluctuating net pressures, defined by the difference between external and internal pressures, are given by Eq.(A6.15) for convenience. For buildings such as free-standing canopy roofs, where the top and bottom surfaces are both exposed to wind, the peak wind force coefficients $\hat{C}_{\mathrm{C}}$ are derived directly from the actual peak values of pressure differences, as shown in section A6.2.7.

External pressure coefficients provided in the Recommendations correspond to the most critical positive and negative peak pressures on each part of a building irrespective of wind direction. Therefore, when the wind loads are calculated by considering the directionality of wind speeds, the peak pressure or force coefficients for each wind direction are needed, which should be determined from appropriate wind tunnel experiments or some other method12).

The subject area A_{C} depends on the item to be designed. When designing the finishing of roofs and external walls, the supported area of the finishing is used, and when designing the supports of the finishing, the tributary area of the supports is used.

A6.1 Wind speed and velocity pressure

A6.1.1 Velocity pressure

The velocity pressure, which represents the kinetic energy per unit volume of the air flow, is the basic variable determining the wind loading on a building.. It corresponds to the rise in pressure from the free stream (atmospheric ambient static pressure) to the stagnation point on the windward face of the building, and is defined as $(1/2)\rho U^2$, where U is the wind speed.

It is only necessary to consider the velocity pressure as the basic variable of wind loading when static effects of the wind are examined. However, it is more appropriate to adopt wind speed as the basic variable when dynamic wind effects are under discussion. Thus, wind speed is adopted in the recommendations as the basic variable for calculating wind loading. The design velocity pressure, q_{H}, which is based on the design wind speed U_{H} at the reference height H, is defined in Eq.(A6.1).

Air density ρ varies with temperature, ambient pressure and humidity. However, the influence of humidity is usually neglected. In these recommendations, the air density is taken as $\rho = 1.22$ (kg/m^3), which corresponds to a temperature of 15°C and an ambient pressure of 1013 hPa.

A6.1.2 Design wind speed

The wind speed at a construction site is a function of its geographical location, orography or large-scale topographic features (e.g. mountain ranges and peninsulas) as well as the ground surface conditions (e.g. size and density of obstructions such as buildings and trees), and small-scale topographic features (e.g. escarpments and hills). The height above ground level is also a factor. Of these factors, the geographical location and large-scale topographical features are reflected in the values of basic wind speed U_0 and wind directionality factor K_{D}. The influences of surface roughness, small-scale topographical features and elevation are reflected in the wind speed profile factor E_{H}.

Designers are required to decide the wind load level by considering the building's social importance, occupancy, economic situation and so on. This is represented by the return period conversion factor k_{rW}. The basic wind load defined in 2.2 is that corresponding to the 100-year-recurrence wind speed, which is calculated from Eq.(A6.2) by substituting $k_{\mathrm{rW}} = 1$. The wind directionality factor K_{D}, a newly introduced parameter in this version, makes the design more rational by considering the dependencies of the wind speed, the frequency of occurrence of extreme wind and the aerodynamic property on wind direction. The wind directionality factor K_{D} is affected by the frequency of occurrence and the routes of typhoons, climatological factors, large-scale topographic effects and so on.

If the design ignores wind directionality effects, the design wind speed U_{H} can be calculated by substituting $K_{\mathrm{D}} = 1$ in Eq.(A6.2).

A6.1.3 Basic wind speed

The basic wind speed U_0 is the major variable in Eq.(A6.2) for calculating the design wind speed. The wind speed at a construction site is influenced by the occurrence of typhoon and monsoon, the longitude and latitude of the location and large-scale topographical effects. The basic wind speed reflects the effects of these factors. The value of the basic wind speed corresponds to the 100-year-recurrence 10-minute-mean wind speed over a flat and open terrain (category II) at an elevation of 10m. Figure A6.1.1 shows the procedure for making the basic wind speed map. As the first step of the procedure, data from different metrological stations were adjusted or corrected to reduce them to a common base considering the directional terrain roughness. Then extreme value analyses were conducted for mixed wind climates of typhoon winds and non-typhoon winds. For typhoon winds, a Monte-Carlo simulation based on a typhoon model was also conducted for each meteorological station in Japan. Although the analysis was conducted with consideration of wind directionality effect, the basic wind speed was considered as a non-directional value. Instead, the wind directionality effect was reflected by introducing the wind directionality factor, which is defined as the wind speed ratio for a certain wind direction to the basic wind speed, as defined in A6.1.4.

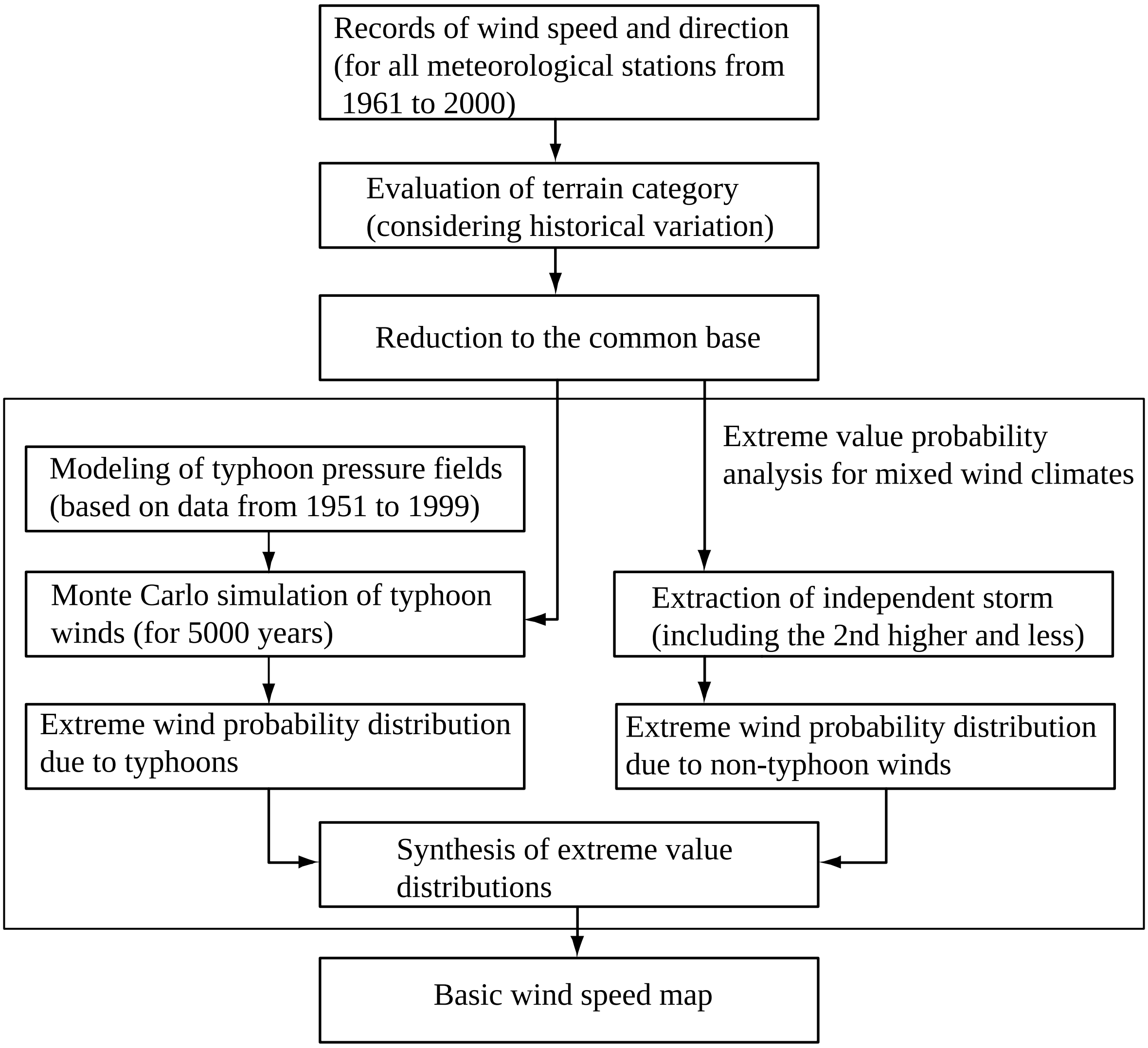


Figure A6.1.1 Procedure for making basic wind speed map

1) Data for analysis

Data of wind speed, wind direction and anemometer height from the Japan Meteorological Business Support Center (Daily observation climate data from 1961-2000, Observation history at metrological stations) were used for analysis. The daily observation climate data from 1961-1990 and the Geophysical Review of 1951-1999 by the Japan Meteorological Agency were referred for modeling the pressure fields and tracks of typhoons, respectively. For homogenization of the wind speed records, data measured by different types of anemometers were corrected to those of propeller type anemometers.

2) Evaluation of directional terrain roughness and homogenization of wind speed

The wind speed records at the meteorological stations were homogenized, that is to say, converted into data at a height of 10m over terrain category II by utilizing a method for evaluating the terrain roughness from the pseudo-gust factor (ratio of daily maximum instantaneous wind speed divided by daily maximum wind speed) and elevation of the measurement point. The details of the method are as follows. The pseudo-gust factors were first averaged according to the year and wind direction. Then, referring to the averaged pseudo-gust factors, a terrain roughness category was identified in which the same gust-factor was given using the profiles of mean wind speeds (defined in A6.1.5) and turbulence intensity (defined in A6.1.6). For this calculation, the terrain roughness category was treated as a continuous variable.

Figure A6.1.2 shows examples of the annual variance of terrain roughness for four dominant wind directions measured at Fukuoka Meteorological Station, in which the symbols are for the calculated values and the lines are the results of linear approximation. The value of roughness category was assumed to be between I and V. This shows that the roughness category changes due to urbanization and the roughness category varies with wind direction.

Historical changes of the directional terrain roughness were utilized for homogenization of wind speed records at meteorological stations and calibration of wind speeds near the ground surface in the extreme value analysis and the typhoon model.

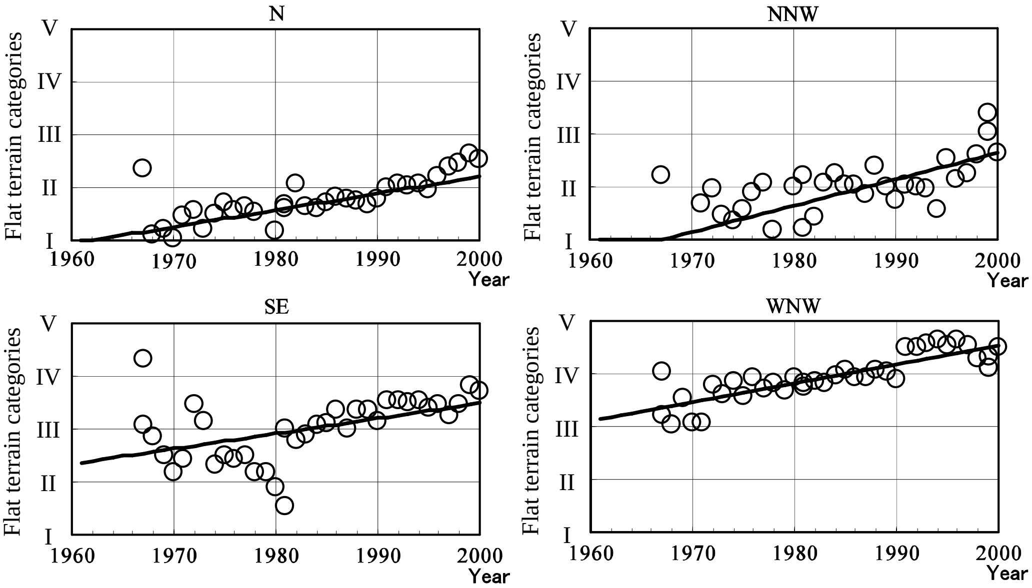


Figure A6.1.2 Examples of evaluation for terrain roughness

3) Extreme value analysis in mixed wind climates

The extreme value analysis in mixed wind climates was applied to extreme wind data generated by different wind climates, for instance, typhoons and monsoons. In this method, the extreme wind records were divided into groups and independently fitted by extreme value distributions, and the combined distribution was obtained assuming the independency of each extreme distribution.

Based on typhoon track data, the measuring records were divided into typhoon and non-typhoon winds, that is, if it was within 500 km of the typhoon center, the wind climate was considered as typhoon, and otherwise as non-typhoon. The wind speed data measured in a typhoon area were analyzed by Monte-Carlo simulation based on a typhoon model to obtain the extreme value distribution, while those measured in a non-typhoon area were analyzed by the modified Jensen & Franck method in which wind speed data smaller than the highest value were also included as independent storms for analysis.

4) Typhoon simulation technique

In Japan, typhoons are the dominant wind climates generating strong winds that need to be taken into account in wind resistant design, due to their high wind speeds and large influence areas. An average of 28 typhoons occur annually, of which roughly 10% land. Typhoons sometimes do not pass near metrological stations, so severe wind damage may occur without large wind speeds being observed. In order to improve the instability of the statistical data (sampling error), a typhoon simulation method was adopted for evaluating the strong wind caused by typhoons.

Figure A6.1.3 shows a general procedure of this typhoon simulation method. The pressure fields of typhoons are modeled by several parameters, i.e. central pressure depth, radius to maximum winds, moving speed, etc. The non-exceedance probability of strong wind in the target area is evaluated by generating virtual typhoons according to the results of statistical analysis of pressure field parameters. This Monte-Carlo simulation method is considered in recommendations of other countries. For example, in the ASCE standard, simulation is required as a principle for evaluation of the design wind speed in hurricane-prone regions. In this standard, the simulation results were adopted as the value of basic wind speed. In order to improve the accuracy of typhoon simulation, correlations between gradient winds and near-ground winds and correlations among parameters of typhoon pressure fields in each area are considered.

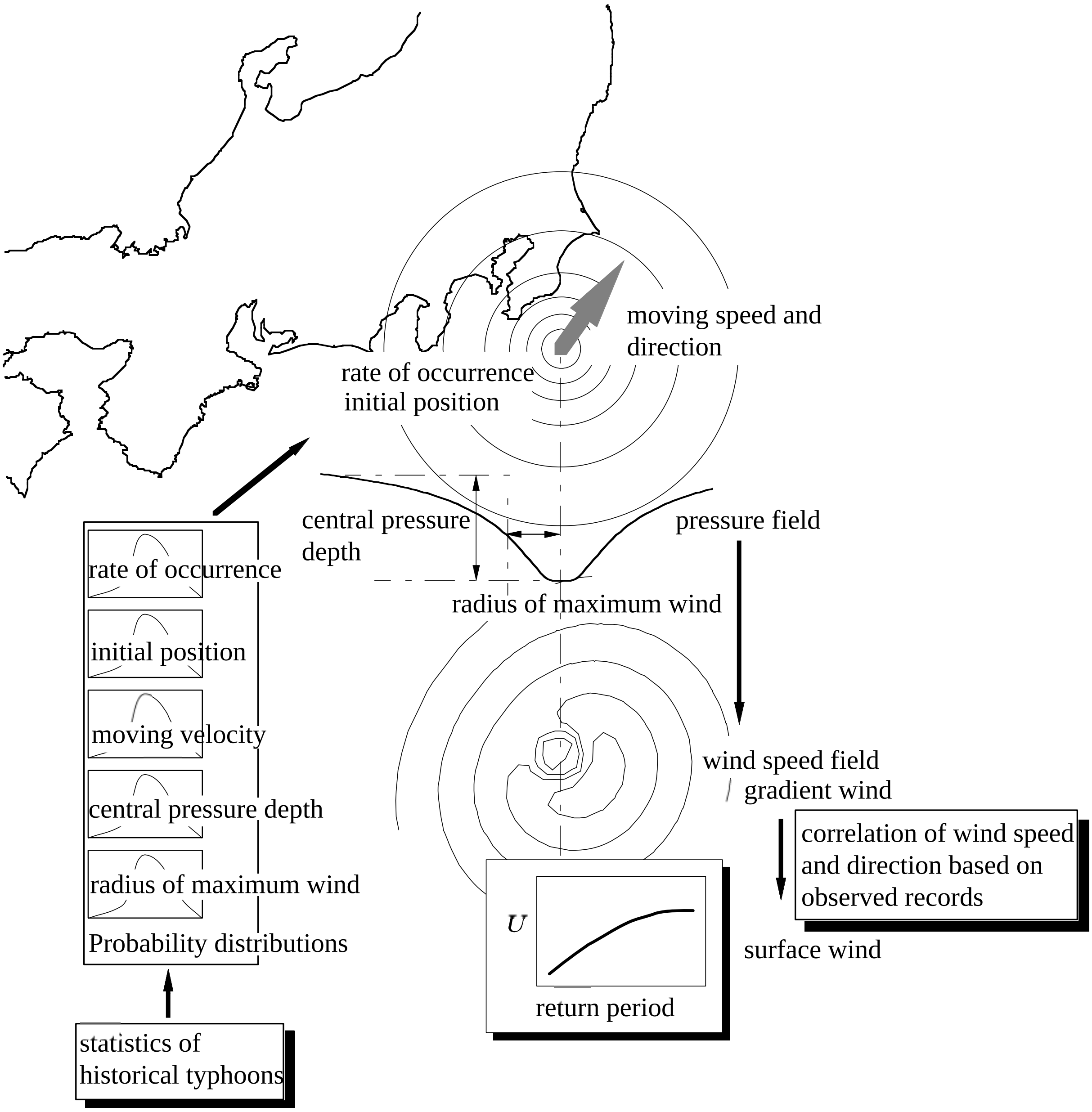


Figure A6.1.3 General procedure for typhoon simulation

The non-exceedance probability of the annual maximum wind speed caused by a typhoon was obtained from the typhoon simulation. For strong wind not caused by a typhoon, extreme value analysis was conducted on data observed from 1961-2000. The results obtained from typhoon and non-typhoon conditions were combined to evaluate the return period of annual maximum wind speed. Figure A6.1.4 shows an example of the maximum wind speed evaluated at K city.

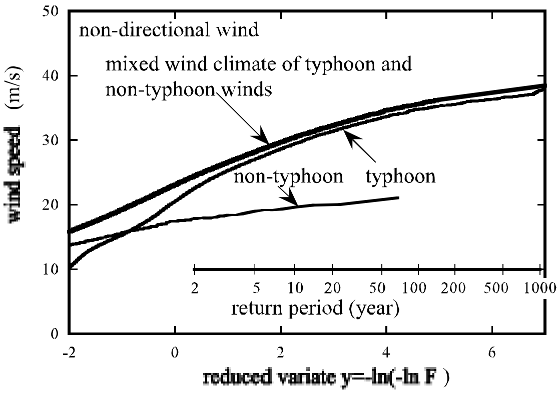


Figure A6.1.4 Example of maximum wind speed evaluated at K city

5) Map of basic wind speed

The contour line of 100-year-recurrence wind speed was somewhat complicated even though the data obtained in 4) had been homogenized according to surface roughness, wind direction, etc. This was assumed to be due to the influences of local topography and structures surrounding the metrological station and the applicability of the homogenization models. To remove such local effects, spatial smoothing was conducted.

In addition, the lower limit of wind speed was set to 30m/s. It is difficult to include the effects of tornado and downburst in the analysis.

6) 100-year-recurrence wind speed in winter

100-year-recurrence wind speed in winter is necessary for combination of wind loads and snow loads. As for the basic wind speed, 100-year-recurrence wind speed in winter reflects only the effects of large-scale topography. Figure A6.1.5 is a spatially smoothed wind speed map made for the 100-year-recurrence wind speed at metrological stations during the snow season (from December to March). The procedure for making this map is the same as that for Fig.A.6.1.1, except that the typhoon simulation method is not used. Thus, the wind directionality factor should not be used ($K_{\mathrm{D}} = 1$) here. For return period factor k_{rW} mentioned in A6.1.7, there are small differences in λ_{U} among wind speeds in winter for different meteorological stations. An average value of $\lambda_{\mathrm{U}} = 1.1$ can be applied for calculating k_{rW} in Eq.(A6.12).

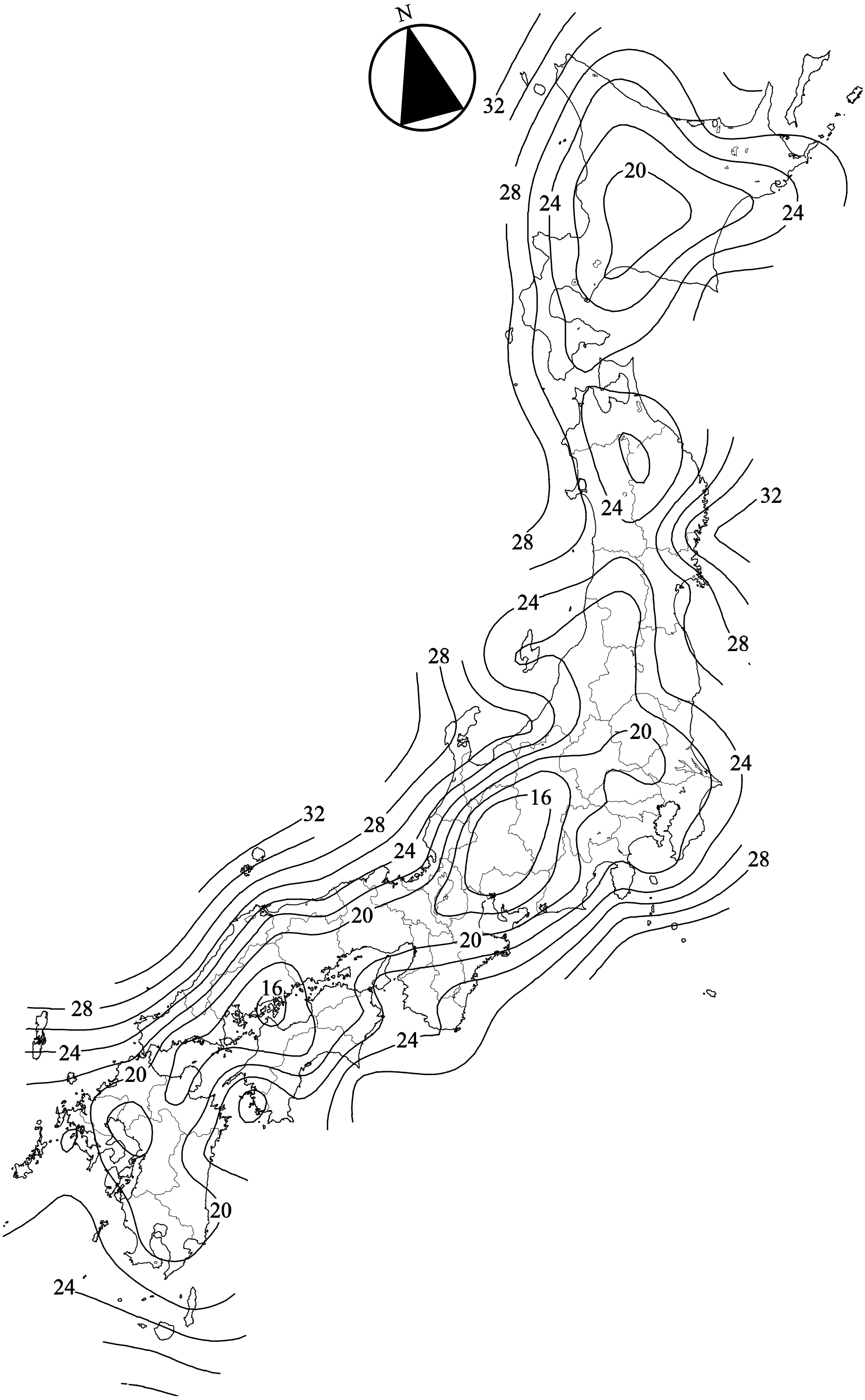


Figure A6.1.5 100-year-recurrence 10-minutes mean wind speed at 10m above ground over a flat and open terrain in winter (m/s)