INTERNATIONAL STANDARD

ISO 4354

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Wind actions on structures

Actions du vent sur les structures

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 4354 was prepared by Technical Committee ISO/TC 98, *Bases for design of structures*, Subcommittee SC 3, *Loads, forces and other actions.*

Annexes A to F of this International Standard are for information only.

Introduction

This International Standard is intended as a model to be used as guidelines for drafting national standards. The data in the annexes are only examples and are not intended to be complete.

Wind actions on structures

1 Scope

This International Standard describes the actions of wind on structures and specifies methods for calculating characteristic values of wind loads for use in designing buildings, towers, chimneys, bridges and other structures, as well as their components and appendages. The loads are suitable for use in conjunction with ISO 2394 and other International Standards concerned with wind loads.

Structures of an unusual nature, size or complexity (e.g. suspension bridges and guyed masts) may require special engineering study; some guidance is given on the limitations of this International Standard in these cases.

2 Normative reference

The following standard contains provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the edition indicated was valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent edition of the standard indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 2394:—[1], *General principles on reliability for structures.*

3 Symbols

Symbol	Quantity	Unit
A	area	m^2
A_s	cross-sectional area	m^2
A_s/A	solidity ratio	1
a	decay coefficient	1
a_p	peak acceleration	m/s^2
B	background response factor	1
b	breadth of structure	m
C_{aer}	aerodynamic damping coefficient	1
C_D	drag coefficient (force coefficient in the along-wind direction)	1
C_{dyn}	dynamic response factor	1

1) To be published. (Revision of ISO 2394:1986)

Symbol	Quantity	Unit
C_{exp}	exposure factor	1
$C_{exp, mod}$	modified exposure factor	1
C_f	force coefficient	1
C_{fig}	aerodynamic shape factor	1
$C_{fig, ext}$	external shape factor	1
$C_{fig, int}$	internal shape factor	1
C_p	pressure coefficient (time and spatially averaged)	1
$C_{p, l}$	time-averaged local pressure coefficient	1
C_1, C_2	vortex shedding coefficients	1
$C_{n, \infty}$, $C_{t, \infty}$	force coefficients for infinitely long member	1
D	diameter	m
d	width of building	m
F_h	horizontal deck load	N
F_m	force on member	N
F_{v1} F_{v2}	traffic loads	N
F_v	vertical deck load	N
F_I	force on windward girder	N
F_{II}	force on leeward girder	N
f_0	natural frequency (first mode)	Hz
g_w	statistical peak factor (for the loading effect)	1
H	hill height	m
h	height of structure	m
h_{ref}	reference height	m
h_t	height of truss	m
h_{v1}	height of vehicle above truss	m
h_{v2}	height of truss above deck level	m
I_u	turbulence intensity	1
k_β	reduction factor for sharp-edged members	1
k_{l, z_0}	scale factor of the logarithmic law	1
k_{p, z_0}	scale factor of the power law	1
k_{red}	reduction factor	1
k_x	shielding factor	1
L	turbulent length	m
L_H	half hill length	m
l	length of member	m
l_B	length of bridge	m
l_v	length of vehicle	m
m	mass	kg
m_l	mass per unit length	kg/m
N	return period	year
Q	squared reduced velocity	m/s
q	velocity pressure	Pa
q_x	reduced velocity pressure	Pa

Symbol	Quantity	Unit
q_{hcr}	critical velocity pressure at the top of the structure	Pa
q_{ref}	reference velocity pressure	Pa
$q(N)$	velocity pressure with return period of N	Pa
R	resonant response	1
Re	Reynolds number	1
S, S'	spectral energy factors	1
Sc	Scruton number	1
Sr	Strouhal number	1
T	averaging time	s
v	wind velocity	m/s
v_{hcr}	critical wind velocity at the top of the structure	m/s
v_{peak}	peak wind velocity	m/s
v_{ref}	reference wind velocity	m/s
v_z	velocity at height above ground, z	m/s
W	wind force	N
W_m	mean loading effect	1
W_p	peak loading effect	1
w	wind force per unit area	Pa
w_L	wind force per unit length	N/m
x	distance	m
y_0	maximum amplitude of structure	m
z	height above ground	m
z_0	roughness length of terrain	m
α	roof slope	°
β	index of the power law	1
γ_w	partial safety factor	1
ΔS_z	"speed-up" factor	1
$\bar{\delta}$	mean deflection	m
ζ	damping ratio	1
ζ_{aer}	aerodynamic damping ratio	1
ζ_{str}	structural damping ratio	1
ρ_{air}	mass density of air	kg/m³
ρ_{bldg}	average mass density of the building superstructure envelope	kg/m³
σ_w	root mean square loading effect	1
ν	cycling rate	Hz
ϕ_i	ratio of the dynamic deflection of the structure at point "i" to the maximum amplitude of the structure	1

4 Wind actions

Wind actions which shall be considered in the design of a structure may produce the following:

a) excessive forces or instability in the structure or its structural members or elements;

b) excessive deflection or distortion of the structure or its elements;

c) repeated dynamic forces causing fatigue or structural elements;

d) aeroelastic instability, in which motion of the structure in wind produces aerodynamic forces augmenting the motion;

e) excessive dynamic movements causing concern or discomfort to occupants or onlookers.

5 Wind force per unit area

For the actions referred to in clause 4 a), b), c) and e), the wind forces per unit area are, in principle, determined from a relationship of the general form:

$$w = q_{\text{ref}} \cdot C_{\text{exp}} \cdot C_{\text{fig}} \cdot C_{\text{dyn}} \qquad \ldots (1)$$

The wind force per unit area is assumed to act statically in a direction normal to the surface of the structure or element, except where otherwise specified, e.g. with tangential frictional forces. Both internal and external forces shall be considered.

The effects of wind from all directions shall be considered.

For some structures it may be appropriate to represent the wind forces by their resultants. These resultants shall include alongwind (drag), crosswind (lift), torsional and overturning actions. Different magnitudes and distributions of the wind force may be necessary to evaluate the actions described in clause 4 a), b), c) and e).

6 Reference velocity pressure, q_{ref}

Velocity pressure is defined by the expression:

$$q = \frac{1}{2} \rho_{\text{air}} v^2 \qquad \ldots (2)$$

The reference velocity pressure q_{ref} is normally the specified value of the velocity pressure for the geographical area in which the structure is located. It refers to a standard exposure (i.e. roughness, height and topography), averaging time and annual probability of recurrence (or recurrence interval). In some situations, the reference velocity pressure may be specified as varying with direction.

Analysis procedures and recommended values are given for information in annex B.

In certain cases, critical loading may occur at values of q differing from that specified above. These critical values of q (with reference to a height h) are denoted q_{hcr} and are substituted for q_{ref}. These cases are discussed in annex E.

7 Exposure factor, C_{exp}

The exposure factor accounts for the variability of the velocity pressure at the site of the structure due to

a) the height above ground level,

b) the roughness of the terrain, and

c) the shape and slope of the ground contours in undulating terrain.

The value of the exposure factor may vary with wind direction.

Recommended values of the exposure factor are given for information in annex C.

8 Aerodynamic shape factor, C_{fig}

The aerodynamic shape factor is the ratio of the aerodynamic pressure on the surface of the structure to the velocity pressure. The latter is normally the product of the exposure factor and the reference velocity pressure.

The aerodynamic shape factor normally refers to the mean (time averaged) value of the pressures but, in certain applications (when the mean is very small), it may refer to other statistical measures such as the peak pressure or root mean square pressure. It may refer to a point pressure, a resultant or an average pressure over an area. It is influenced by the geometry and shape of the structure, the exposure, the relative wind direction, the Reynolds number and the averaging time.

Enclosed structures will be subjected to internal pressures determined by the size and distribution of openings and by any pressurization, mechanical or otherwise. Allowance should be made for these by combining the aerodynamic shape factors for the external pressures with those for the internal pressures.

Aerodynamic shape factors may be determined from one of the following sources:

a) annex D;

b) appropriate wind tunnel tests, as described in annex D;

c) other codes or standards, provided that appropriate adjustment is made for any discrepancies in averaging time and exposure from those used in this International Standard, and provided that adequate provision is made for a dynamic response factor.

9 Dynamic response factor, C_{dyn}

The dynamic response factor accounts for the following actions of the wind:

a) fluctuating pressures due to random wind gusts acting for an interval of time shorter than that specified in the averaging time for the reference velocity pressure, and acting over all or part of the surface area of the structure;

b) fluctuating pressures in the wake of the structures (vortex shedding forces), producing resultant forces acting transversely as well as torsionally and longitudinally;

c) fluctuating pressures induced by the motion of the structure due to the wind.

Information on these effects and appropriate values of the dynamic response factor are given for information in annex E.

Resonance may amplify the response to these forces in certain wind-sensitive structures. Such structures are characterized by their lightness, flexibility and low level of structural damping. Indications of the wind-sensitive characteristics of structures are provided in annex E.

10 Criterion for aeroelastic instability

For structures affected by wind actions specified in clause 4 d) that cause aeroelastic instability, it must be shown that the performance of the structure, without further application of the load factor, is acceptable up to a wind velocity somewhat higher than v_{ref}. Unless alterative rational procedures are available, this wind velocity shall be taken as $\sqrt{\gamma_w} \cdot v_{ref}$, where γ_w is the normal partial safety factor and v_{ref} is the reference design wind velocity (corresponding to q_{ref} as defined in clause 6). A discussion of this problem is given in annex E.

11 Methods of analysis

Two methods or levels of design analysis are recommended in this International Standard which are referred to as the simplified method and the detailed method. In addition, for certain wind-sensitive structures, special supplementary studies are recommended.

The simplified method for estimating wind loading is described fully in annex A. It provides simplified values of the exposure factor C_{exp}, aerodynamic shape factor C_{fig} and dynamic response factor C_{dyn}, consistent with those in annexes C, D and E. The method is intended for the design of cladding of most normal structures. It can also be used for the design of the main structural system of structures meeting all the criteria given in annex A.

For the detailed method of estimating wind loading, the appropriate values of the exposure factor, shape factor and dynamic response factor are given in annexes C, D and E. This method is principally of assistance in assessing the dynamic response of the structure, the influence of unusual exposure, and the characteristics of more complex aerodynamic shapes.

Structures sensitive to wind include those that are particularly flexible, slender, tall or of light weight. Unusual geometry may also give rise to an unexpectedly large response to wind. In these instances, supplementary studies by an expert in the field are recommended and these may include wind-tunnel tests. These tests may be used to establish details of the overall structural loads and the distribution of external local pressures. Details of suitable testing procedures are given in annex D.

Alternative methods of analysis to those recommended in this International Standard may be permitted provided it can be demonstrated that the level of safety achieved is generally equivalent to that achieved in this International Standard. Guidance on the level of safety is given in annex F.

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Annex A
(informative)

Simplified method of analysis

A.1 Criteria

This simplified method is intended for the design of the cladding of most normal structures. It can also be used for the design of the main structural system of structures which meet all of the following criteria.

a) The structure is less than 15 m in height above ground.

b) The structure is not unusually exposed for any wind direction; i.e. it is not situated near a hillcrest nor headland.

c) The structure is relatively rigid. For habitable buildings, the deflections under wind loading, calculated by the simplified method, should be less than 1/500 of the height of the structure or of the relevant span. For industrial structures (e.g. chimneys), higher deflections may be acceptable depending on the serviceability requirements.

A.2 General relationship

The general relationship for determining the wind loading is given by equation (1) (see clause 5):

$$w = q_{ref}\ C_{exp}\ C_{fig}\ C_{dyn}$$

The values of the factors to be used are given below.

A.3 Reference velocity pressure, q_{ref}

This is defined in annex B, for a given region.

A.4 Exposure factor, C_{exp}

This is determined from table A.1 for each height range in question.

On coastal or particularly exposed, flat, open sites, the values of C_{exp} given in table A.1 should be increased by a factor. This factor will normally be in a range from 1,2 to 1,4. If detailed information is not available, the value 1,3 is recommended.

Table A.1 — Exposure factor, C_{exp} — Simplified method

Applicability	Range of height of structure, h m	C_{exp}
Structural design	$0 < h \leq 5$ $5 < h \leq 10$ $10 < h \leq 15$	0,9 1 1,1
Cladding design	$0 < h \leq 20$ $20 < h \leq 25$ $25 < h \leq 35$ $35 < h \leq 45$ $45 < h \leq 55$ $55 < h \leq 65$ $65 < h \leq 80$ $80 < h \leq 100$	1,2 1,3 1,4 1,5 1,6 1,7 1,8 1,9

A.5 Combined aerodynamic shape factor and dynamic response factor, $C_{fig}C_{dyn}$

The combined wind loading on external and internal surfaces should be based on the *combined* factor as follows:

$$(C_{fig}C_{dyn})_{com} = (C_{fig}C_{dyn})_{ext} - (C_{fig}C_{dyn})_{int} \qquad \text{. . . (A.1)}$$

A.5.1 Walls and roofs

The products of the internal aerodynamic shape factor and dynamic response factor, $(C_{fig}C_{dyn})_{int}$, are given in table A.2.

Table A.2 — Internal pressures — Shape factors and dynamic response factors

Type of structure	$C_{fig, int}$	$C_{dyn, int}$	$(C_{fig}C_{dyn})_{int}$
Buildings with large openings (e.g. sheds with an open side; industrial buildings with shipping doors or ventilators having a high probability of being open; large glass windows exposed to damage from debris)	− 0,7	2	− 1,4
Buildings with openings less than 1 % of total wall area, not uniformly distributed (e.g. most enclosed buildings with windows and doorways)	− 0,7	1	− 0,7
Buildings without large openings, and only small openings of less than 0,1 % of total area (e.g most tall buildings which are normally sealed and ventilated mechanically; exceptionally, low buildings such as windowless warehouses with door systems designed to withstand the wind)	0 − 0,3	1 1	0 − 0,3

For low buildings with flat or gable roofs, the product of the external aerodynamic shape factor and the dynamic response factor, $(C_{fig}C_{dyn})_{ext}$, is presented in figures A.1, A.2 and A.3.

The cladding, fastenings, secondary structural elements (girts and purlins) and individual roof or wall panels should be designed using factors given in figure A.2 for walls and figure A.3 for roofs. Reductions for larger tributary areas may be made.

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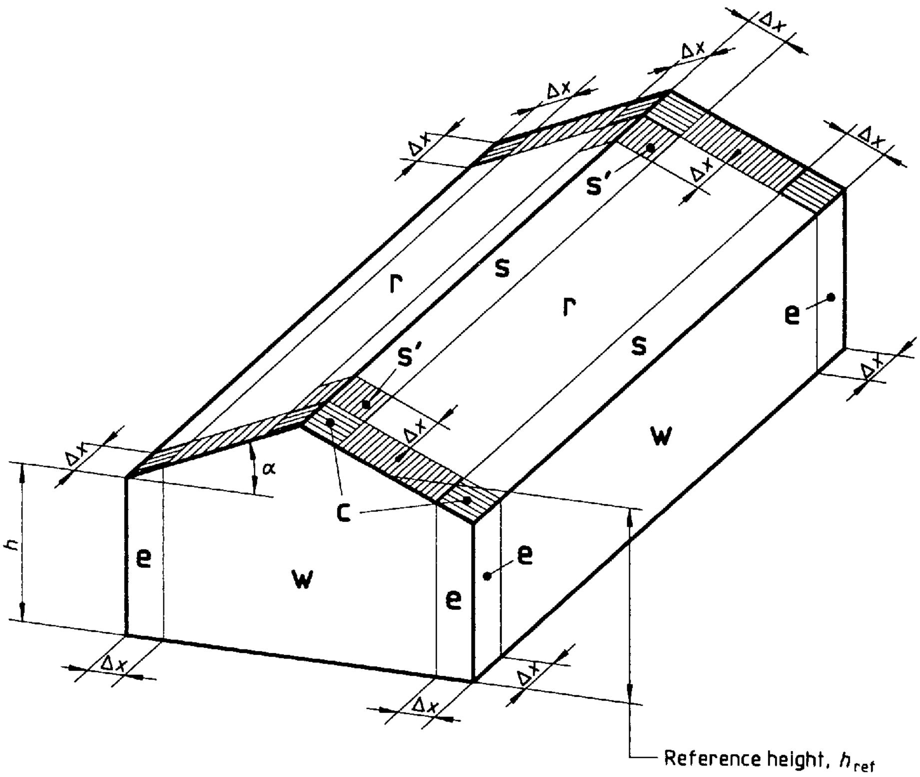

10 ° < a < 45 °

Figure A.1 — Surfaces of walls and roofs

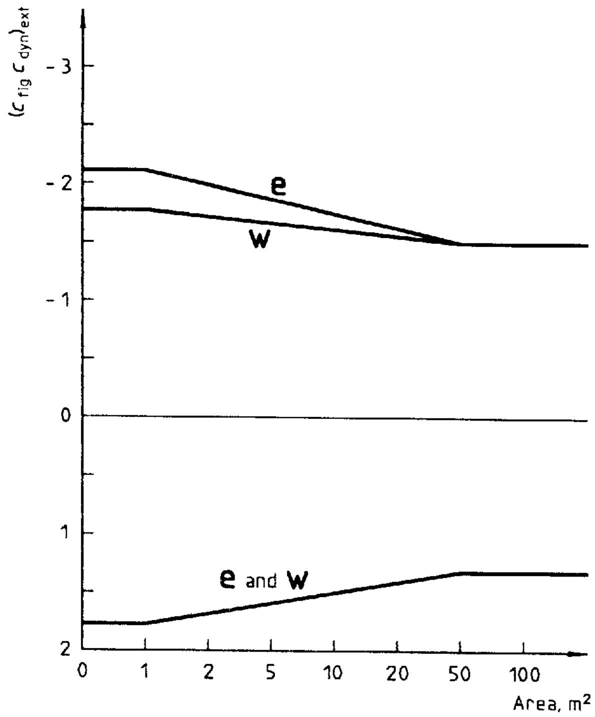

Figure A.2 — Values of $(C_{fig}C_{dyn})_{ext}$ for low buildings — Walls

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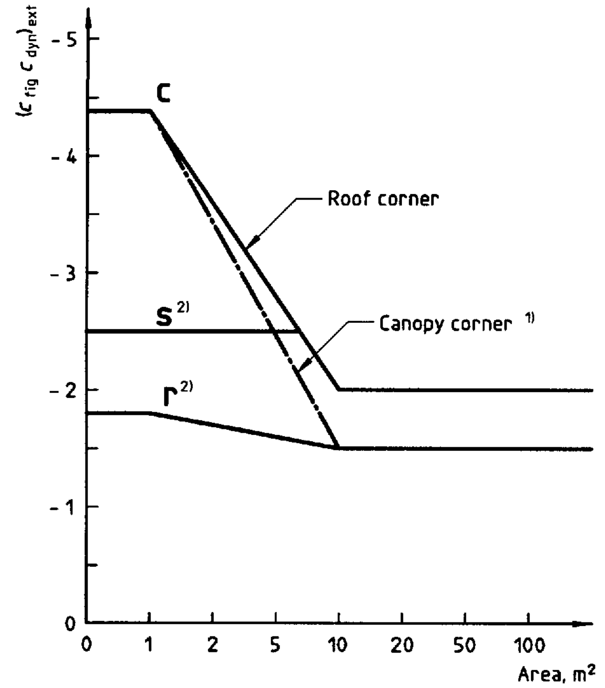
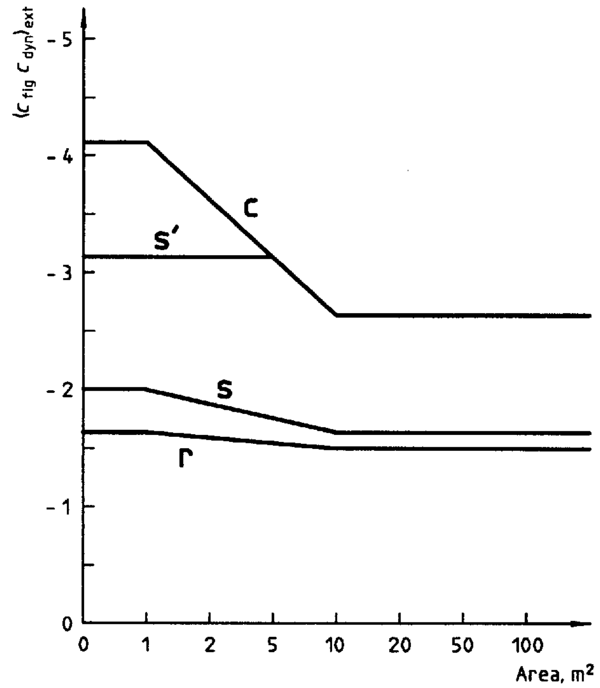
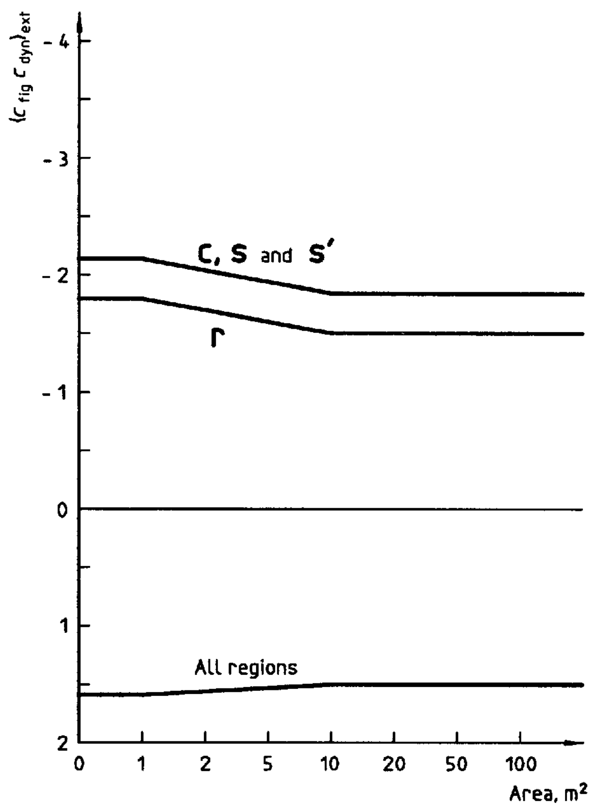


1) Canopy coefficients include contributions from both upper and lower surfaces.
2) **s** and **r** are applicable to both roofs and canopies.

a) 0° < α ≤ 10°



b) 0° < α ≤ 30°



c) 30° < α ≤ 45°

Figure A.3 — Values of $(C_{fig}C_{dyn})_{ext}$ for low buildings — Roofs

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For estimation for the loads for the design of the foundations and footings, excluding anchorages, 70 % of the values of $(C_{fig}C_{dyn})_{ext}$ may be used.

The abscissa areas in figures A.2 and A.3 are the design tributary area within the specified zone.

The reference height h_{ref} for pressures is the mid-height of the roof or 6 m, whichever is the larger.

D_x is 10 % of the smallest horizontal dimension or 40 % of height h, whichever is the smaller. Also, where $D_x \geqslant 1$ m, $D_x \geqslant 4$ % of the smallest horizontal dimension.

A.5.2 Frames

Figure A.4 shows the wind directions to be considered on the surfaces of framed low buildings.

Factors given in tables A.3 and A.4 for the frame loading may be used only if more than one roof or wall surface participates in the action, and only for estimating loading on rigid frames, total roof uplift, sliding shear or overturning. The design should consider wind acting from any direction.

For estimation of the loads for the design of the foundations and footings, excluding anchorages, 70 % of the values of $(C_{fig}C_{dyn})$ may be used.

The building should be designed for all wind directions. Each corner should be considered in turn as the windward corner shown in figure A.4. For all roof slopes, load case A and load case B1 (see tables A.3 and A.4) are required as two separate loading conditions to generate the wind actions. If the roof slope is 20° or more, a third loading condition B2 is also required (see table A.4).

The value of D_y is 6 m or 2 D_x, whichever is the greater.

Table A.3 — Values of $(C_{fig}C_{dyn})_{ext}$ for load case A: Winds generally perpendicular to ridge

Roof slope	Building surface							
a	1	2	3	4	1E	2E	3E	4E
0° to 5°	0,75	- 1,3	- 0,7	- 0,55	1,15	- 2	- 1	- 0,8
20°	1	- 1,3	- 0,9	- 0,8	1,5	- 2	- 1,3	- 1,2
30° to 45°	1,05	0,4	- 0,8	- 0,7	1,3	0,5	- 1	- 0,9
90°	1,05	1,05	- 0,7	- 0,7	1,3	1,3	- 0,9	- 0,9

Table A.4 — Values of $(C_{fig}C_{dyn})_{ext}$ for load cases B1 and B2: Winds generally parallel to ridge

Load case	Roof slope a	Building surface											
		1	2	3	4	5	6	1E	2E	3E	4E	5E	6E
B1	< 20°	0	- 1,3	- 0,7	0	0,75	- 0,55	0	- 2	- 1	0	- 1,15	- 0,6
B2	⩾ 20°	- 0,65	- 1,3	- 0,7	- 0,85	0	0	- 0,9	- 2	- 1	- 0,9	0	0

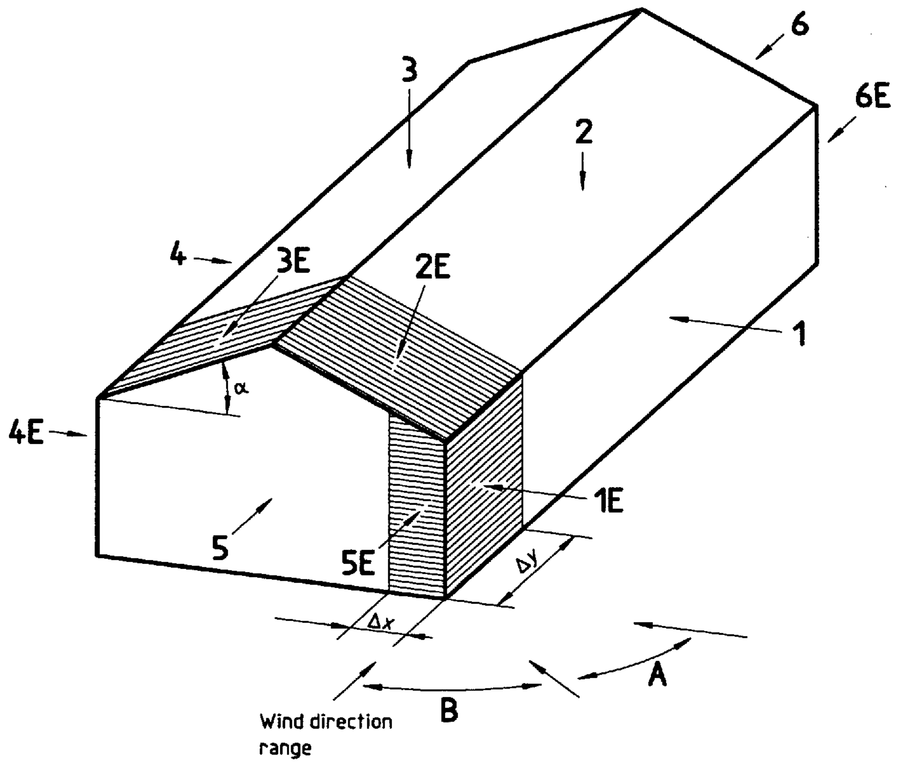

Figure A.4 — Wind on surfaces of frames

A.6 Aerodynamic shape factor: other structures and members

For other structural shapes and members, the values of aerodynamic shapes factors are given in annex D for external and internal pressures.

A.7 Dynamic response factor, C_{dyn}

If the dynamic response factor is not given in conjunction with the aerodynamic shape, its value should be taken as follows:

for cladding:	2,5
for main structure (including anchorages):	2
for foundations and footings[2]:	1,4

2) See annex E.

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Annex B
(informative)

Reference velocity pressure, q_{ref}

B.1 General

This annex recommends procedures for determining the reference velocity pressure q_{ref} for the calculation of the wind load w stated in clause 5. This reference velocity pressure should be determined from meteorological data for the region, obtained over a number of years. The exact nature of these data varies from country to country. In some instances, the measured data may refer to the velocity pressure itself but, more often, they refer to some measure of the wind velocity [see equation (2)]. Furthermore, the measurements frequently deviate from the standard exposure of 10 m above open terrain[3] and averaging time of 10 min used in this International Standard. For example, short-duration gust wind velocities are the standard measurement made in some countries, while mean velocities averaged over periods from 1 min to 1 h are standard in others. There is therefore a need for methods to reconcile these data with the basis recommended. Such methods are outlined below.

B.2 Definitions of q_{ref}

The reference velocity pressure q_{ref} recommended for use in this International Standard, as stated in clause 6, corresponds to the mean velocity pressure over open terrain at an equivalent elevation of 10 m, averaged over a period of approximately 10 min and with a recurrence interval (return period) of once-in-50 years. This is an annual probability of 0,02 and corresponds to the most likely greatest wind velocity in a 50-year period. A period of this order is conventional in wind loading applications. (Under some circumstances it may be related to a nominal lifetime or in-service period of the structure.)

Because wind near the surface of the earth is turbulent and gusty, use of the 10-min mean velocity pressure permits a stable definition of the wind over an area which is larger than the structure and over a period longer than the "response time" of the structure.

Values of q_{ref} for the region of application are inserted in table B.1 when this International Standard is used as the model for a national standard.

Table B.1 — Reference wind velocity pressures

<table>
<tr><th rowspan="4">Location</th><th colspan="3">Wind velocity pressure
kPa</th><th>Wind velocity
m/s</th></tr>
<tr><td rowspan="2"></td><td colspan="2">Return period, N, years</td><td rowspan="3">v_{ref} 1)</td></tr>
<tr><td>10</td><td>100</td></tr>
<tr><td>q_{ref} 1)</td><td>$q_{(10)}$</td><td>$q_{(100)}$</td></tr>
<tr><td colspan="5">NOTE — Values are to be entered in this table when this International Standard is used as the model for a national standard.</td></tr>
<tr><td colspan="5">1) It is recommended that 0,3 kPa be taken as a minimum value.</td></tr>
</table>

The reference velocity pressure over return periods other than the 50-year value adopted can be found using the expression

$$q(N) = q(10) + [q(100) - q(10)][(\ln N/\ln 10) - 1]$$

3) For a definition, see *Guide to Metrological Instruments and Methods of Observation*. No. 8, Geneva: WMO, 1983, clause 6.6.2.

... (B.1)

where N is the return period, in years. Velocity pressures for the construction period should be obtained by consultation with the local meteorological authorities.

In some locations the reference velocity pressure may vary significantly with direction due to the topography, terrain roughness and the prevailing wind climate; in these cases the reference velocity pressure may be specified by direction and should be illustrated by a map of the region concerned.

B.3 Wind velocities and averaging intervals

It may be necessary in some countries to use other wind velocity measurements and, in these cases, careful correction is necessary. As a guide, the wind velocities over different averaging intervals corresponding to various values of q_{ref} are given in table B.2. (This allows comparison with other codes.)

Table B.2 — Relationship between reference velocity pressure, q_{ref}, and peak wind velocity, v_{peak}, measured over short time intervals in open terrain at an equivalent elevation of 10 m

q_{ref} 1) kPa	v_{peak} m/s			
	Averaging time			
10 min	10 min	1 h	1 min (or "fastest mile")	3 s
0,3	21	22,4	27	33
0,4	25	25,8	31	39
0,5	27	28,9	35	43
0,6	30	31,6	38	47
0,7	32	34,2	41	51
0,8	35	36,5	44	55
0,9	37	38,7	47	58
1	39	40,8	50	61
1,1	41	42,8	52	64
1,2	43	44,7	54	67
1,3	44	46,5	56	70
1,4	46	48,3	58	73
1,5	48	50	61	75

NOTE — Intermediate values may be interpolated.

1) Assuming air density $\rho_{air} = 1,2$ kg/m³.

B.4 Air density

A representative value of air density to be used in the calculation of velocity pressure is 1,2 kg/m³, but this is affected by altitude and is a function of the temperature and pressure to be expected in the region during a wind storm. A suitable value should be obtained from a meteorological authority familiar with the region.

B.5 Methods of analysis

To determine the reference velocity pressure, extreme-value analysis should normally be applied. The steps in this procedure are as follows.

a) Annual maximum velocity pressures (or velocities) should be determined from the data for each year of record; 10-min mean values are preferred.

b) The values of velocity or velocity pressure are corrected for exposure and averaging time; in the case of velocities, the corrected values should be converted to velocity pressure.

c) Extreme-value analysis is applied to the annual extremes as outlined in standard references. The Fisher-Tippet type 1 distribution is recommended for this purpose.

d) From the statistical distribution "best" fitting the data, the required reference velocity pressures for the 1/50 and other annual probabilities are estimated.

Alternative methods of determining the extreme values (e.g. from the rate of occurrence of individual storms or the parent population) are available and may be used. Special treatment of extreme values in regions of hurricane winds may be required.

B.6 Properties of wind turbulence

Other properties of the wind are needed in the development of the wind load, such as the intensity, the spectrum and scale of turbulence. These properties are described in annex E in the context in which they are needed.

B.7 Tornadoes and thunderstorms

This International Standard does not include the special effects of tornadoes and thunderstorms. The ratio between mean and gust speeds adopted here to derive C_{dyn} is not applicable to regions dominated by tornadoes and thunderstorms.

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Annex C
(informative)

Exposure factor, C_{exp}

C.1 General

The exposure factor for use in this International Standard and referred to in clause 7 describes the variation in the reference velocity pressure with height, terrain roughness and topography.

C.2 Wind profiles over flat terrain

Terrain roughness is aerodynamically described in terms of a roughness length z_0 which characterizes the size and distribution of the obstacles around and over which the wind blows. Representative flat terrains and their velocity profile parameters are represented in table C.1. Characteristic terrains can encompass a range of roughness length as shown in figure C.1. Values of roughness length other than those given in table C.1 may be adopted if considered more appropriate.

Table C.1 — Representative flat terrains and their velocity profile parameters

Terrain description	Logarithmic profile		Power law profile	
	Roughness length m z_0	Scale factor $k_{l,\,z_0}$	Index β	Scale factor $k_{p,\,z_0}$
Open sea	0,003	0,021	0,11	1,4
Open terrain[1)]	0,03	0,030	0,14	1,0
Suburban, woodland	0,3	0,041	0,22	0,5
City centre	3	0,058	0,31	0,16
NOTE — Profiles matched at 30 m.				
1) Recommended values for normal usage.				

The exposure factor at height z recommended for use in this International Standard is defined either by a logarithmic profile or by a power law profile. The logarithmic profile is given by

$$C_{exp,\,z} = k_{l,\,z_0}\left[\ln(z/z_0)\right]^2 \qquad \text{... (C.1)}$$

in which values of $k_{l,\,z_0}$ for different roughness lengths z_0 and terrains are given in table C.1.

This can be closely matched to the power law profile:

$$C_{exp,\,z} = k_{p,\,z_0}(z/10)^{2\beta} \qquad \text{... (C.2)}$$

in which β and $k_{p,\,z_0}$ depend on ground roughness and are given in table C.1

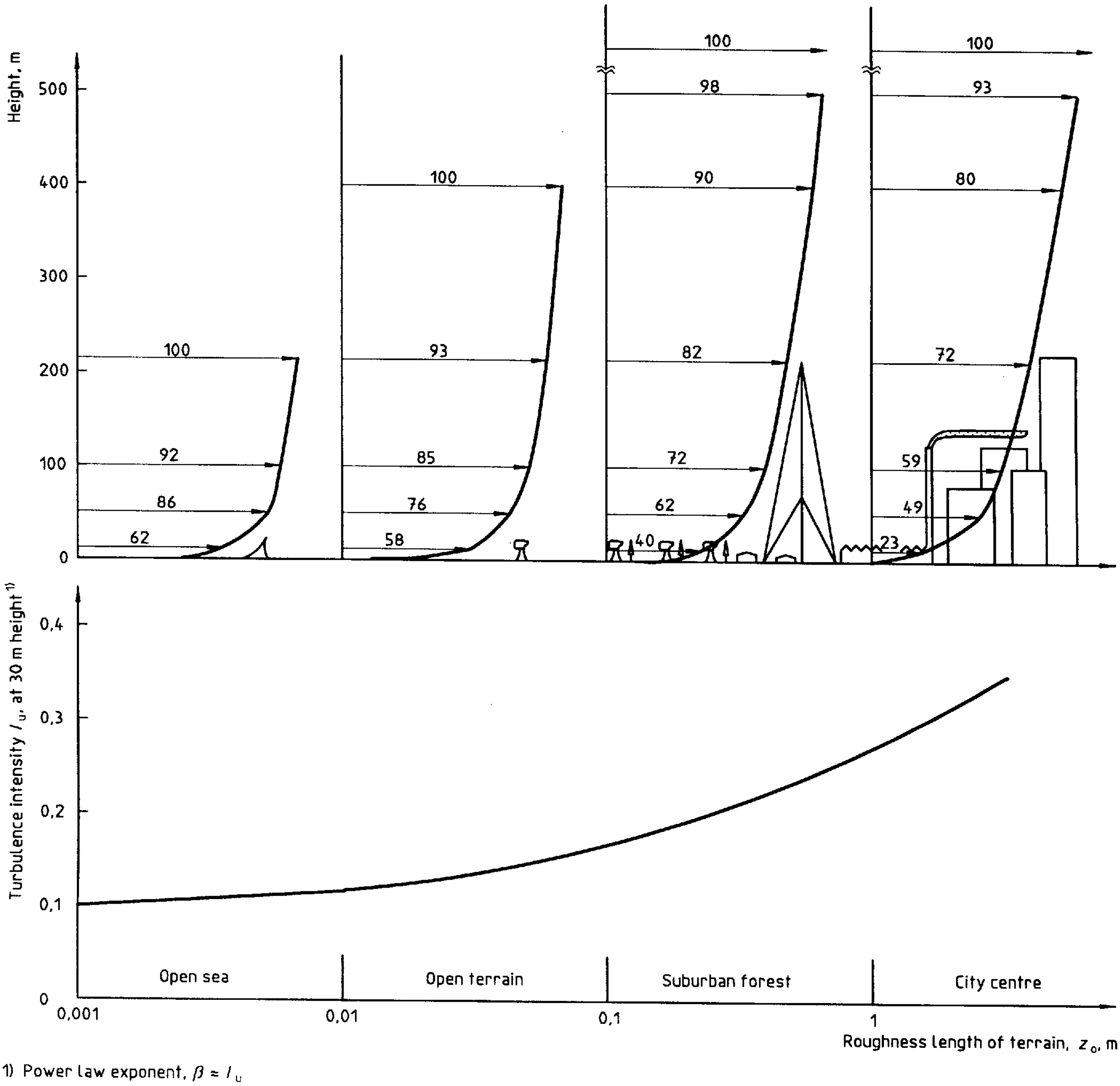

Figure C.1 — Variation of mean wind velocity with height over rough terrain

It should be noted that these two profiles can be matched closely over any given height range using the expression

$$\beta = \left[\ln(z_1/z_0)\right]^{-1} \qquad \ldots \text{(C.3)}$$

where z_1 is a representative height (30 m, or the average height of construction, is often appropriate).

C.3 Change in roughness

The transition of the flow from one roughness to another takes a distance of approximately 5 km for the height ranges affecting most structures. Hence the reduction in wind velocity associated with the transition to rougher terrain should only be assumed if terrain of the stated roughness exists for this distance, or if suitable transition formulae are adopted.

C.4 Speed-up over hills and escarpments

For structures situated in hilly, undulating terrain, the speed-up of the mean wind velocity over hills and escarpments is an important consideration. The exposure factor at height z is equal to that over flat terrain multiplied by a factor $(1 + \Delta S_z)^2$ where ΔS_z is the "speed-up" factor for the mean wind velocity.

This is illustrated in figure C.2. Near the crest, and within a distance $|x| < k_{red} L_H$ the exposure factor is modified to become:

$$C_{exp,mod} = C_{exp,z}\left[1 + \Delta S_{z,max}\left(1 - \frac{|x|}{k_{red} L_H}\right) e^{-(az/L_H)}\right]^2 \quad \text{... (C.4)}$$

where

$C_{exp,z}$ is the exposure factor over flat terrain given in equation (C.1) or (C.2);

$\Delta S_{z,max}$ is the relative "speed-up" factor at the crest near the surface;

a is a decay coefficient for the decrease in "speed-up" with height.

The values of a and $\Delta S_{z,max}$ depend on the shape and steepness of the hill. Representative values for the maximum "speed-up" factor on hillcrests are given in table C.2 and the definition of the hill height H and half hill length L_H are given in figure C.2.

It should be noted that the speed-up principally affects the mean wind velocity and not the turbulence. (Allowance for effects on C_{dyn} of speed-up due to hills is given in E.2.)

Table C.2 — Parameters for maximum speed-up over low hills

Hill shape	$\Delta S_{z,max}$	a	k_{red}	
			$x < 0$	$x > 0$
Two-dimensional ridges (or valleys with H negative)	2 H/L_H	3	1,5	1,5
Two-dimensional escarpment	1,8 H/L_H	2,5	1,5	4
Three-dimensional axisymmetrical hills	1,6 H/L_H	4	1,5	1,5
NOTE — For $H/L_H > 0,5$, assume $H/L_H = 0,5$.				

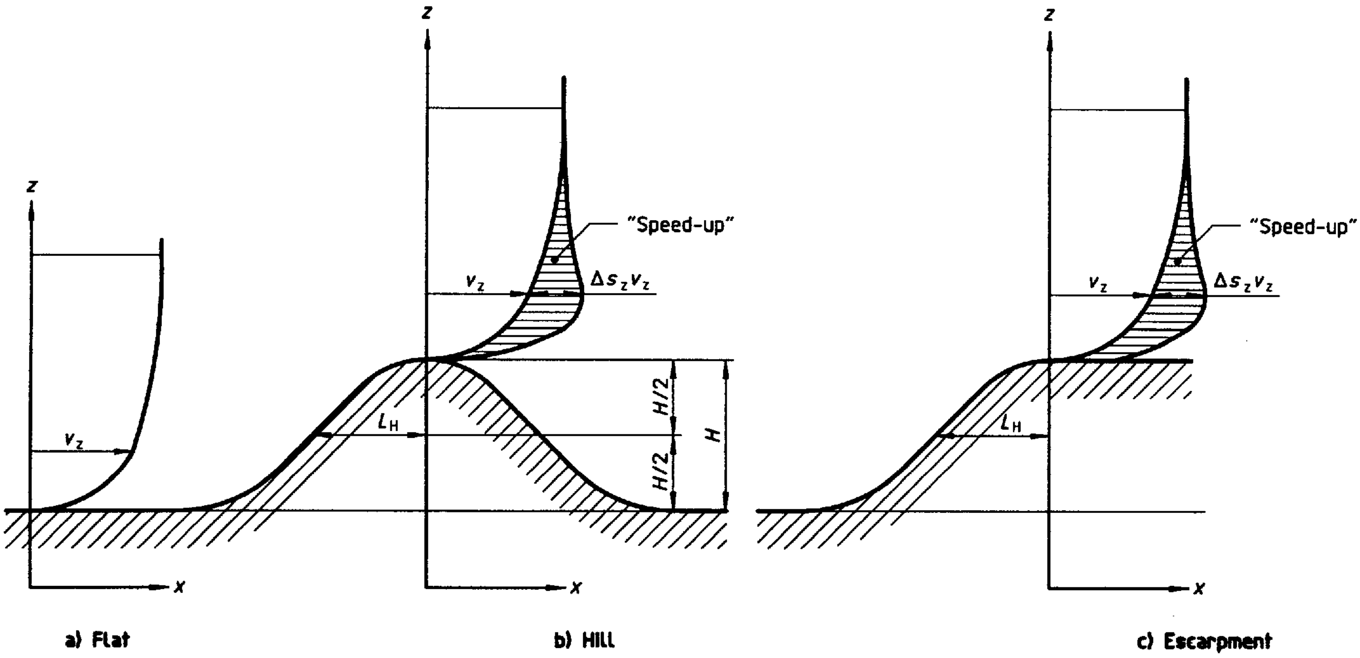

Figure C.2 — Definitions for wind "speed-up" over different terrain

Annex D
(informative)

Aerodynamic shape factor, C_{fig}

D.1 General

The aerodynamic shape factor, C_{fig}, is a dimensionless aerodynamic coefficient which expresses the aerodynamic pressures induced on the structure and its elements as a ratio of the velocity pressure (normally $q_{ref}C_{exp}$) in the oncoming flow. Normally the shape factor refers to the mean (time-averaged) pressures but, in some special applications (for pressures transverse to the flow, for example, where the mean is small or zero), other statistical measures such as the root mean square value are used. These special applications are noted in the text. The shape factors used in this International Standard fall into three categories.

a) Aerodynamic shape factors (pressure coefficients) used in defining local pressures on the structure acting normal to the surface and denoted $C_{p,\,l}$.

b) Aerodynamic shape factors (force coefficients) used in defining resultant forces over specified areas of the structure. These are normally the simple area average of the components of the pressure coefficients acting in the direction of the required resultant force.

c) Aerodynamic shape factors defining higher-order resultant actions of the pressures, such as moments and torques.

Factors appearing under b) and c) are defined in the section where they are used.

D.2 Reference exposure factors

The shape factors are normally defined in conjunction with exposure factors for the same level in the flow or at some fixed reference level (e.g. the top of the building). With all the cases as well as with force coefficients, the level of the exposure factor is specified in the context in which it is used. Shape factors for some local pressures are defined in conjunction with exposure factors at fixed levels in order to simplify their numerical description.

In the case of design of surface-cladding elements and frame structures, the acting pressures should be considered as the combined action of the pressures on the inside and exterior surfaces.

D.3 Wind tunnel testing procedures

Shape factors should normally be determined from wind-tunnel testing on models. The dynamic factors C_{dyn} should, where possible, also be obtained in these tests. These wind tunnels must adequately model the conditions existing at the actual site.

In general cases, for three-dimensional structures, it is necessary to model the important features of the natural boundary layer, namely its mean velocity variation with height and the structure of turbulence. In some particular cases it is acceptable to use shape factors determined from wind-tunnel tests carried out in flow deviating from the natural wind (e.g. in the smooth uniform flow of aeronautical wind tunnels). This approach may be appropriate for the design of sections of tall masts. Aerodynamic shape factors of sharp-edged shapes are generally insensitive to wind velocity. With curved shapes such as circular cylinders, there is some sensitivity to Reynolds number scaling, as well as surface roughness and turbulence characteristics.

D.4 Forms of presentation

For some shapes having a curved cross-section, such as chimneys, there can be significant effects due to Reynolds number, as well as the intensity and scale of turbulence. These influences should be kept in mind in defining values of C_{fig} for such shapes.

In the definition of the shape factors used in this International Standard, it was noted that they are normally related only to the time-averaged pressures and forces or otherwise to the root value if the mean is small. Fluctuations in the flow due to gusts naturally induce additional fluctuations in pressure. The additional effect these may have on the response is accounted for by the dynamic response factor C_{dyn} (described in clause 9 and annex E). Shape factors in use in various national standards and codes and in the literature may be defined using different averaging times for the wind velocity pressure, different flow conditions, different reference areas and reference heights. Special care is needed in adopting other values to ensure consistency with the method of this International Standard. Reference values for use with the shape factors in this International Standard are defined in the section in which they are given.

Examples of shape factors given in this annex are taken from the commentary to the National Building Code of Canada, 1985. The range and accuracy of shape factors are improving continuously. The best available shape factors should be included and amendments issued when appropriate.

The information on external and internal shape factors (including dynamic response factors) given in clause A.5 and figure D.1 covers the requirements for the design of the cladding and the structure as a whole for a variety of simple building geometries. The values of the shape factors given in figure D.1 are either time- and spatially-averaged shape factors, C_{fig}, or simply time-averaged local pressure coefficients, $C_{p,l}$. In clause A.5 dealing with low buildings, values of the product $C_{fig}C_{dyn}$ are given; this is the form in which they are used, and the form of the basic wind-tunnel data from which they were derived. These are cases in which there is no requirement for the separate factors, so resonant amplification of the response can normally be disregarded.

D.5 Internal shape factors

The internal shape factors, $C_{fig,\ int}$, define the effect of wind on the air pressure inside the building and are important in the design of both cladding elements and the overall structure. In the case of a dominant opening, the internal shape factor will be approximately equal to the external shape factor at the opening. In other instances, the magnitude of the shape factors tends to be uncertain owing to the influence of either intended or (in the case of window breakage) unintended openings and the normal ventilation of the building envelope. As a consequence, internal shape factors may be wide-ranging.

In the face of these uncertainties, an appropriate treatment of internal pressures for both high and low structures is to use the values for $C_{fig,\ int}$ and C_{dyn} given in annex A, table A.2. This choice depends on whether there are openings and whether small openings are truly uniformly distributed. In this context, a large opening is one which offers an opening to the wind exceeding that of the estimated total leakage area of the entire building surface, including the roof. Such an opening may result from deliberate intent or failure to design an element (such as a door or window) to resist wind. For typical buildings, whose background leakage area is 0,1 % of the total surface area, an opening greater than about 1 % of the relevant wall would constitute a large opening.

The designer is then faced with three basic categories.

a) Buildings with large openings for which a dynamic factor is required. Normally the range of $C_{fig,\ int}$ of ± 0,7 should be used, as given in table A.2, but it is sufficient in most cases to use a C_{dyn} value of 2. Such buildings would include, for example, sheds with one open side, industrial buildings with shipping doors, ventilators or similar openings having a high chance of being open, and buildings with large glass areas which may be exposed to damage by flying debris.

b) Buildings without large openings but having small openings not uniformly distributed. C_{dyn} = 1, although the full range of $C_{fig,\ int}$ (± 0,7) given in table A.2 should be considered. Examples include most low buildings which, although fairly uniformly sealed, have doorways or windows which may produce a significant imbalance in air leakage.

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c) Buildings without large openings but having small openings (i.e. roughly less than 0,1 % total area) uniformly distributed. $C_{dyn} = 1$. The values of $C_{fig,\ int}$ considered should be the – 0,3 value given in table A.2, except where that alleviates an external load, when $C_{fig,\ int} = 0$ should be used. This latter provision is in the light of research which indicates that the internal pressure fluctuates even within buildings having small distributed openings, and the pressure fluctuations occasionally reach $C_{fig,\ int} = 0$. Such buildings include most high-rise buildings that are sealed and ventilated mechanically, and, exceptionally, lower buildings such as windowless warehouses, with door systems designed to withstand wind.

Transitions between these categories can be found based on ratios of air leakage and opening sizes.

Internal pressures are also affected by mechanical ventilation systems and by a stack effect when inside and outside air temperatures differ. Under normal operations, mechanical systems create differentials across walls somewhat less than 0,1 kPa, but the stack effect for differences in temperature of 40 °C could amount to 0,2 kPa per 100 m of building height.

D.6 "Low" buildings

Annex A refers to low buildings and presents data obtained from systematic boundary layer wind-tunnel studies. In several instances these data have been verified against available full-scale measurements. The factors are based on the maximum gust pressures lasting approximately 1 s and, consequently, include an allowance for the dynamic factor, C_{dyn}. The factors, therefore, represent the product $C_{fig}C_{dyn}$. An innovative feature of these figures is their reference to the tributary area associated with the particular element or member over which the wind pressure is assumed to act. In all cases these coefficients should be combined with the appropriate internal pressures.

Annex A is appropriate for buildings with widths greater than twice their heights and for which the reference height does not exceed 15 m. In the absence of more appropriate data, the values quoted in annex A may also be used for buildings with $h/b < 1$ and a reference height less than 20 m. Beyond these extended limits, figure D.1 should be used.

Annex A presents values of $C_{fig}C_{dyn}$ applicable to those primary structural actions affected by wind pressures on more than one surface, such as in framed buildings. These simplified load distributions were developed to yield as closely as possible the structural actions (horizontal thrust, uplift and frame moments) determined directly from experiment. These results make allowance for the partial loading of gusts.

Annex A is also intended to cover those actions influenced mainly by wind acting over single surfaces, such as the design of cladding and secondary structural members.

D.7 "High" structures

Figures D.1 and D.2 are for use with tall, rectangular structures for which $h/b > 1$. The pressure coefficients given are not multiplied by a dynamic factor, C_{dyn}. It is important to realize that a local pressure coefficient $C_{p,l} = -1$ is applicable to the design of small cladding areas (about the size of a window), which can occur almost anywhere and at any elevation. Recent wind-tunnel tests have shown that regions of high suction are not limited to corners, as indicated previously by available information.

D.8 Protected membrane roofs

In the case of a protected membrane roof, with insulation which is not bonded to the water-proofing membrane, the insulation is not subjected to the same uplift pressure as is applied through the depth of the entire roof assembly, because of air leakage and partial pressure equalization between the top and bottom of the insulation boards. External pressure or uplift due to wind is, therefore, applied to the membrane, which acts as an air barrier between the inside and the outside and prevents pressure equalization.

D.9 Other structures and members

Figures D.3 to D.13 are based on wind tunnel experiments in which the correct velocity profile and turbulence of natural wind were not simulated. Although they should therefore be regarded with caution, the corrections which may be involved are not considered significant for these cases. They are based on the Swiss Society of Engineers and Architects (SIA) standard No.160, *Actions on structures*, published in 1989 (in French and German) and in 1991 (in English).

D.10 Rounded structures

For rounded structures (in contrast to sharp-edged structures), the pressures vary with the wind velocity, depending on the Reynolds number, Re. In figures D.5, D.6, D.9 and D.12, Re is expressed by $D\sqrt{qC_{exp}}$ where D is the diameter of the sphere or cylinder, in metres, and q is the velocity pressure, in kilopascals. To convert to Re, multiply $D\sqrt{qC_{exp}}$ by $2{,}7 \times 10^6$.

The roughness of rounded structures may be of considerable importance. Common well-laid brickwork without parging can be considered as having a "moderately smooth" surface (figure D.5). Surfaces with ribs projecting more than 2 % of the diameter are considered as "very rough". In case of doubt, it is recommended to use those C_{fig} values which result in the greater forces. For cylindrical and spherical objects with substantial stiffening ribs, supports and attached structural members, the shape factors depend on the type, location and relative magnitude of these roughnesses.

D.11 Structural members

In figures D.10, D.11, D.12 and D.13, shape factors with the subscript "∞" are used to indicate that they apply to structural members of infinite lengths and this is multiplied by a reduction factor, k_{red}, for finite lengths of members. If a member projects from a large plate or wall, the reduction factor, k_{red}, should be calculated for a slenderness based on twice the actual length. If a member terminates with both ends in large plates or walls, the reduction factors for infinite length should be used.

D.12 Loads on frames and shielding

For framing members that are located behind each other in the direction of the wind, the shielding effect may be taken into account. The windward members and those parts of the leeward members that are not shielded should be designed with the full pressure, q, whereas the shielded parts of the leeward members should be designed with the reduced pressure, q_x, given in figure D.14.

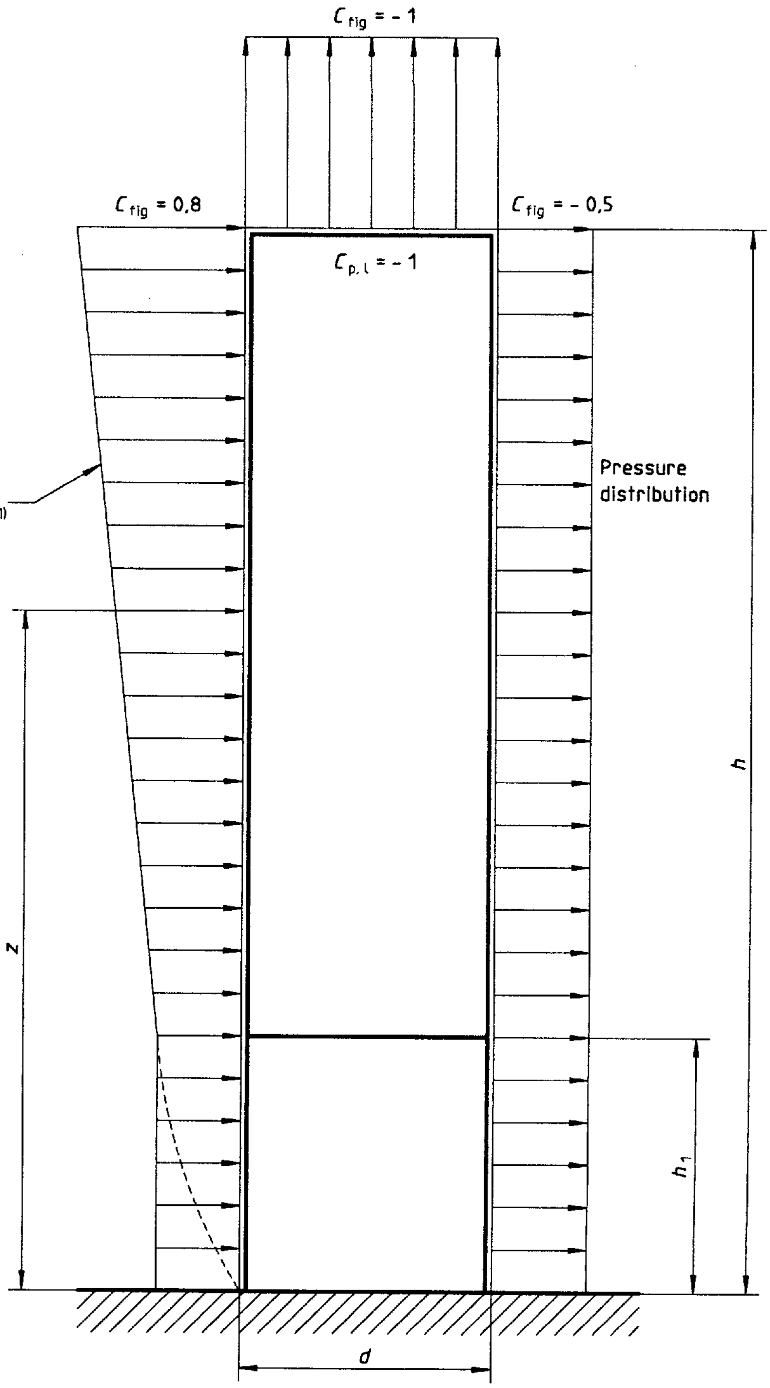
It should be noted that the shape of a structure may change during erection. The wind loads, therefore, may be temporarily higher during erection than after completion of the structure. These increased wind loads should be taken into account using the appropriate coefficients.

For frames made from circular sections with $D\sqrt{qC_{exp}} < 0{,}167$ and $A_s/A > 0{,}3$, the shielding factors can be taken by approximation from figure D.14. If $D\sqrt{qC_{exp}} > 0{,}167$, the shielding effect is small and for a solidity ratio $A_s/A < 0{,}3$, it can be taken into account by a constant shielding factor $k_x = 0{,}95$.

D.13 Partial loading and torsional loading

To allow for the non-uniform and torsional loading effects of transient gusts, buildings are required to be designed for partial loading as well as the fully loaded case. Unless explicit allowance is made for these effects, other load cases should be considered in which up to 50 % of the load specified in this International Standard is removed from any part of the structure. Some structures, such as arch-type roof systems, experience larger stresses under partial loading. Tall buildings should be checked against partial loadings that produce torsional effects. Examples have been encountered in wind-tunnel testing in which torsional effects were even greater than those afforded by a 50 % removal of loads from selected areas of the building. Torsional effects are enhanced when the centre of twist is eccentric from the centre of gravity (inertial loading) or from the centre of area (wind loading, full or partial).

The pressure coefficients in figures D.1 and D.2 refer to pressures acting along the principal axes of rectangular building forms. In some structural systems, more severe effects may be induced when the resultant wind pressures approach the building diagonally. To account for this and also the additional tendency for structures to sway laterally to the wind direction, 75 % of the maximum loads for each of the principal directions should be applied jointly. See also E.3.



1) Windward wall: C_{fig} the pressure coefficient is 0,8 for the entire height. The variation shown in the pressure distribution is due to the variation in exposure factor C_{exp}.

NOTES

1 Wind perpendicular to one wall: for width, use the dimension perpendicular to the wind direction.

2 Wind at an angle to the wall: this condition produces high local suctions on the wall which is at a slight angle to the wind. The coefficient $C_{p,l}$ may occur anywhere over the wall area, but need not be considered in conjunction with the C_{fig} for overall loading. The coefficients $C_{p,l}$ for the roof are given in figure D.2.

3 End walls: pressure coefficients for end walls (parallel to wind direction) are given in figure D.2.

4 Interior pressure: coefficients $C_{fig,int}$ for interior pressures are given in figure D.2.

5 Reference height for exposure factor: for the calculation of both spatially averaged and local pressures, use 0,5 h for the leeward walls, h for the roof and side walls, and the height up to the level under consideration, z, for the windward wall.

6 Height h_1, the height to which C_{exp} is constant, is 10 m for the simplified method and exposure A, 12,7 m for exposure B and 30 m for exposure C.

Figure D.1 — Pressure distribution on flat-roof buildings greater in height than in width (Elevation of building)

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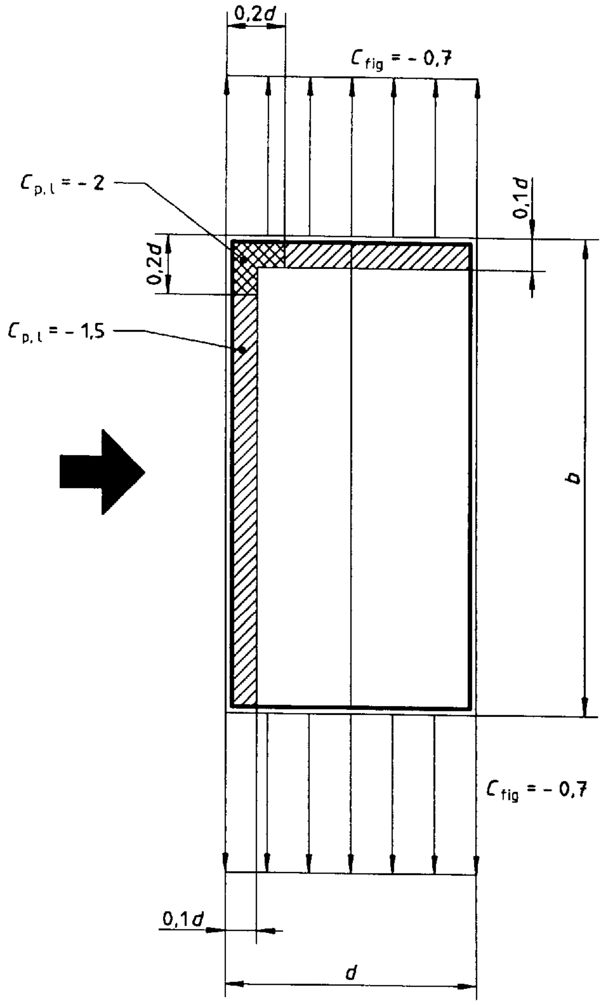


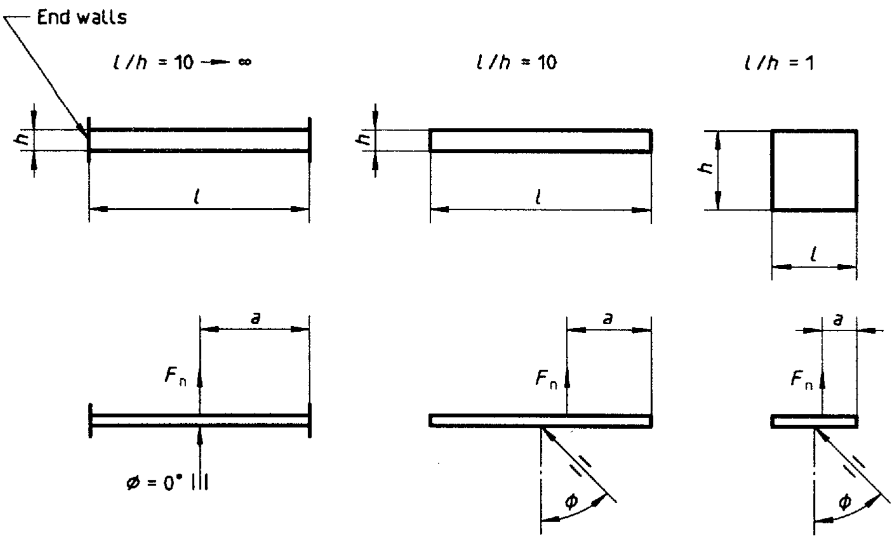
NOTES

1 Local maximum suctions: the factors $C_{p,\,l}$ for the roof surface occur for wind at an angle to one corner, and are used in the design of the roofing itself and its anchorage to the structure. $C_{p,\,l}$ values are not to be added to the C_{fig} value for determining the total uplift on the roof.

2 End walls: the end walls are the ones parallel to the wind direction and have a uniform pressure distribution over the whole building height, except for local maximum suction as indicated in figure D.1.

3 Reference height for exposure factor: for the calculation of external pressures on end walls, use h, the total height of the building. For the calculation of internal pressures, use 0,5 h unless there are dominant openings in the windward wall, in which case use z, the height of the highest of such openings.

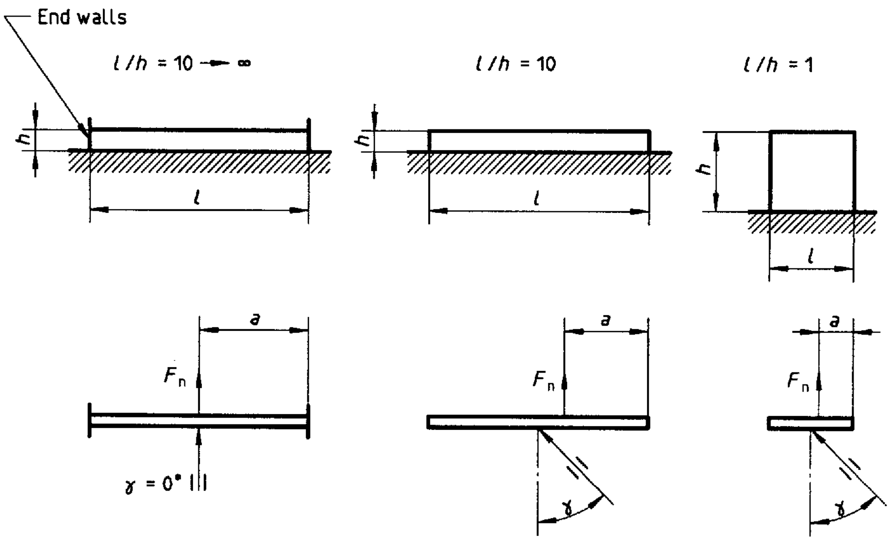
Figure D.2 — Plan view of building — End wall shape factors and local suction maxima on the roof



$$F_n = C_f \cdot q \cdot C_{dyn} \cdot C_{exp} \cdot h \cdot l$$

Force coefficient C_f for walls above ground

l/h	10 ⟶ ∞ (End walls)	10	1
$\phi = 0°$ $a = 0{,}5\ l$	2	1,3	1,15
$\phi = 40°$ $a = 0{,}3\ l$		1,6	
$\phi = 50°$ $a = 0{,}4\ l$			1,8



Force coefficient C_f for walls on the ground

l/h	10 ⟶ ∞ (End walls)	10	1
$\phi = 0°$ $a = 0{,}5\ l$	1,2	1,2	1,1
$\phi = 40°$ $a = 0{,}3\ l$		1,5	
$\phi = 50°$ $a = 0{,}4\ l$			1,5

Figure D.3 — Free-standing plates, walls and billboards

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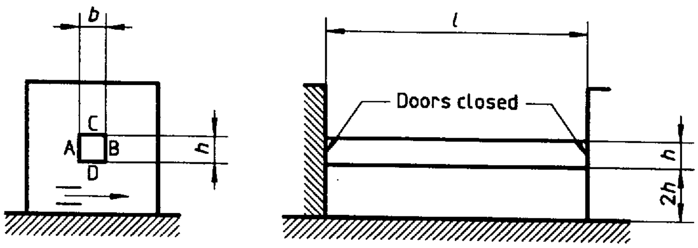


$h : b : l = 1 : 1 : 10$

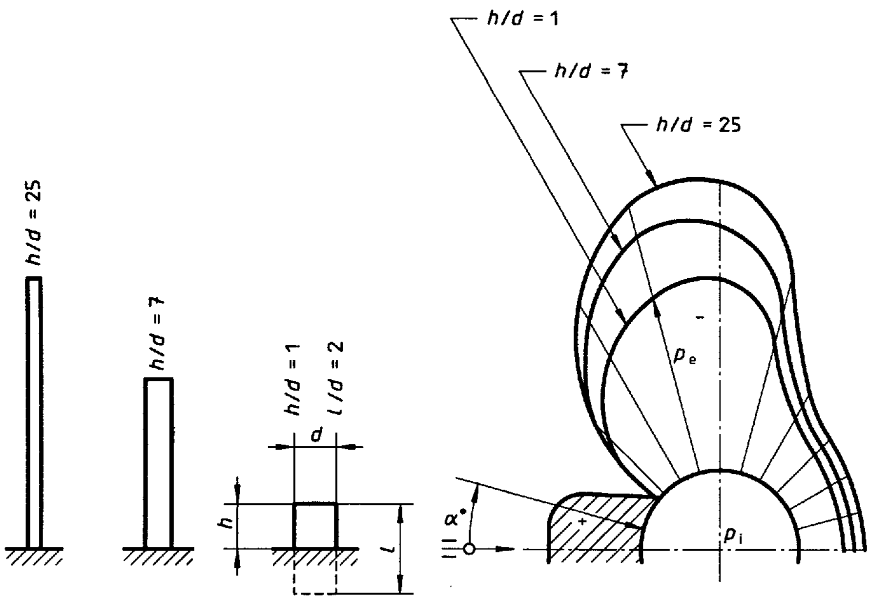
External shape factors, $C_{fig, ext}$

ϕ	A	B	C	D
0°	+ 0,8	− 1,2	− 1,4	− 1,5

Internal shape factors, $C_{fig, int}$

Openings	$\phi = 0°$
Uniformly distributed	− 0,5
Predominating on side A	+ 0,7
Predominating on side B	− 1,1
Predominating on side C	− 1,3

Figure D.4 — Closed passage between large walls



Total force: $F = C_f \cdot q \cdot C_{dyn} \cdot C_{exp} \cdot A$, where $A = d \cdot h$

Force coefficient, C_f for $d\sqrt{qC_{exp}} > 0{,}167$

Cross section and roughness	Slenderness h/d 25	7	1
Moderately smooth (metal, timber, concrete)	0,7	0,6	0,5
Rough surface (rounded ribs $h = 0{,}02d$)	0,9	0,8	0,7
Very rough surface (sharp ribs $h = 0{,}08d$)	1,2	1	0,8
Smooth and rough surface, sharp edges	1,4	1,2	1

External shape factor $C_{fig,\,ext}$ for $d\sqrt{qC_{exp}} > 0{,}167$ and moderately smooth surface

h/d	l/d	α 0°	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°	180°
25	50	+ 1	+ 0,8	+ 0,1	− 0,9	− 1,9	− 2,5	− 2,6	− 1,9	− 0,9	− 0,7	− 0,6	− 0,6	− 0,6
7	14	+ 1	+ 0,8	+ 0,1	− 0,8	− 1,7	− 2,2	− 2,2	− 1,7	− 0,8	− 0,6	− 0,5	− 0,5	− 0,5
1	2	+ 1	+ 0,8	+ 0,1	− 0,7	− 1,2	− 1,6	− 1,7	− 1,2	− 0,7	− 0,5	− 0,4	− 0,4	− 0,4

$\Delta p = p_i - p_e$

where

$p_i = C_{fig,\,int} \cdot q \cdot C_{dyn} \cdot C_{exp}$

$p_e = C_{fig} \cdot q \cdot C_{dyn} \cdot C_{exp}$

Stack fully operating, $C_{fig,\,int} = + 0{,}1$

Stack throttled, $C_{fig,\,int} = - 0{,}8$

Figure D.5 — Cylinders, chimneys and tanks

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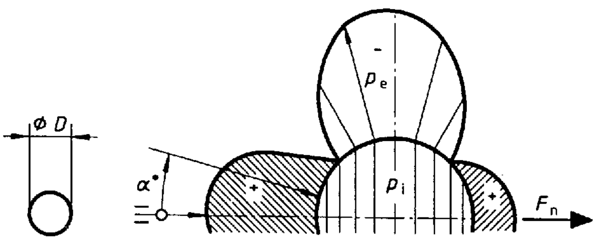


Total force

$$F = C_f \cdot q \cdot C_{dyn} \cdot C_{exp} \cdot A$$

where

$$A = \frac{\pi D^2}{4}$$

Force coefficient

$C_f = 0,2$ for $D\sqrt{qC_{exp}} > 0,8$ and moderately smooth surface

$$\Delta p = p_i - p_e$$

where

p_i for closed tanks is the working pressure

$$p_e = C_{fig} \cdot q \cdot C_{dyn} \cdot C_{exp}$$

External shape factor $C_{fig.\,ext}$, for $D\sqrt{qC_{exp}} > 0,8$ and moderately smooth surface

α												
0°	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°	180°
+ 1	+ 0,9	+ 0,5	− 0,1	− 0,7	− 1,1	− 1,2	− 1	− 0,6	− 0,2	+ 0,1	+ 0,3	+ 0,4

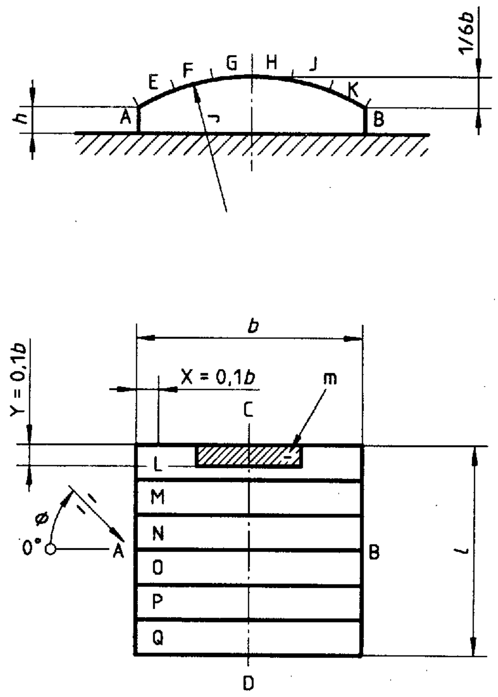
Figure D.6 — Spheres

External shape factors, $C_{fig, ext}$

ϕ	A	B	C	D	E	F	G	H	J	K
0°	+ 0,7	− 0,2	− 0,3	− 0,3	− 0,1	− 0,5	− 0,8	− 0,8	− 0,4	− 0,1
30°	+ 0,6	− 0,3	+ 0,2	− 0,4	− 0,1	− 0,4	− 0,7	− 0,9	− 0,7	− 0,4

Radius $r = 5/6\ b$

$h{:}b{:}l = 1{:}12{:}12$



Shaded area to scale

ϕ	A	B	C	D	L	M	N	O	P	Q
90°	− 0,3	− 0,3	+ 0,9	− 0,3	− 0,8	− 0,7	− 0,5	− 0,3	− 0,1	− 0,1
30°	Section m, $C_{p,l} = -1{,}8$ with minimum $C_{p,l} = -2{,}5$									

Internal shape factors, $C_{fig, int}$

Openings	$\phi = 0°$	$\phi = 30°$	$\phi = 90°$
Uniformly distributed	± 0,2	± 0,2	± 0,2
Window Y open on side A	+ 0,4	+ 0,7	− 1
All doors open on side C	− 0,1	+ 0,6	+ 0,8
Only door X open on side C	− 1,5	+ 0,7	+ 0,4

Figure D.7 — Hangar with curved roof and moderately smooth surface

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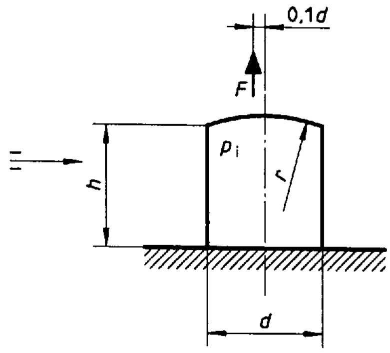
$h{:}d{:}r = 1{:}1{:}1{,}5$



Total force on roof

$F = (p_i - p_e)A$

p_i = working pressure

$p_e = C_{fig} \cdot q \cdot C_{dyn} \cdot C_{exp}$

$A = \frac{\pi}{4} d^2$

External shape factor, $C_{fig,\ ext} = -1$

Figure D.8 — Roof load on smooth closed tank

Force coefficients, C_f

Type of pole, rod or wire	$D\sqrt{qC_{exp}}$ < 0,167	$D\sqrt{qC_{exp}}$ > 0,167
Smooth wires, rods, pipes	1,2	0,5
Moderately smooth wires and rods	1,2	0,7
Fine wire cables	1,2	0,9
Thick wire cables	1,3	1,1

$l/D > 100$

Total force

$F = C_f \cdot q \cdot C_{dyn} \cdot C_{exp} \cdot A$

$A = D \cdot l$

Figure D.9 – Poles, rods and wires

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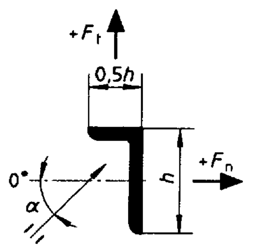
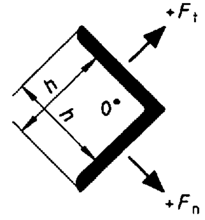
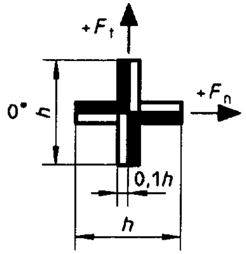
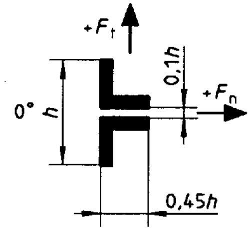
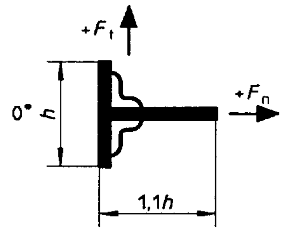
Force coefficients, $C_{n,\infty}$ and $C_{t,\infty}$, for an infinitely long member

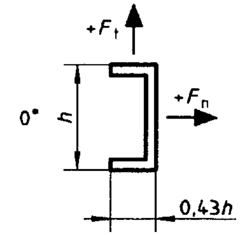




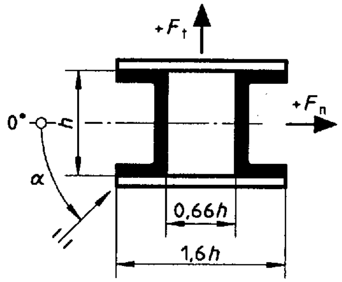


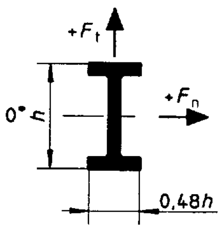


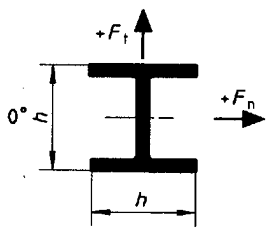


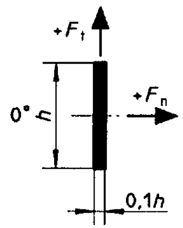


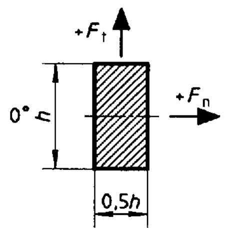
α	$C_{n,\infty}$	$C_{t,\infty}$	$C_{n,\infty}$	$C_{t,\infty}$	$C_{n,\infty}$	$C_{t,\infty}$	$C_{n,\infty}$	$C_{t,\infty}$	$C_{n,\infty}$	$C_{t,\infty}$	$C_{n,\infty}$	$C_{t,\infty}$
0°	+ 1,9	+ 0,95	+ 1,8	+ 1,8	+ 1,75	+ 0,1	+ 1,6	0	+ 2,0	0	+ 2,05	0
45°	+ 1,8	+ 0,8	+ 2,1	+ 1,8	+ 0,85	+ 0,85	+ 1,5	− 0,1	+ 1,2	+ 0,9	+ 1,85	+ 0,6
90°	+ 2,0	+ 1,7	− 1,9	− 1,0	− 0,1	+ 1,75	− 0,95	+ 0,7	− 1,6	+ 2,15	0	+ 0,6
135°	− 1,8	− 0,1	− 2,0	+ 0,3	− 0,75	+ 0,75	− 0,5	+ 1,05	− 1,1	+ 2,4	− 1,6	+ 0,4
180°	− 2,0	+ 0,1	− 1,4	− 1,4	− 1,75	− 0,1	− 1,5	0	− 1,7	± 2,1	− 1,8	0

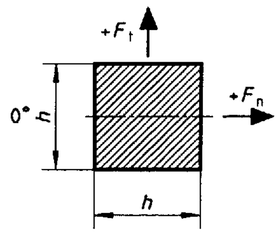












α	$C_{n,\infty}$	$C_{t,\infty}$	$C_{n,\infty}$	$C_{t,\infty}$	$C_{n,\infty}$	$C_{t,\infty}$	$C_{n,\infty}$	$C_{t,\infty}$	$C_{n,\infty}$	$C_{t,\infty}$	$C_{n,\infty}$	$C_{t,\infty}$
0°	+ 1,4	0	+ 2,05	0	+ 1,6	0	+ 2	0	+ 2,1	0	+ 2	0
45°	+ 1,2	+ 1,6	+ 1,95	+ 0,6	+ 1,5	+ 1,5	+ 1,8	+ 0,1	+ 1,4	+ 0,7	+ 1,55	+ 1,55
90°	0	+ 2,2	± 0,5	+ 0,9	0	+ 1,9	0	+ 0,1	0	+ 0,75	0	+ 2

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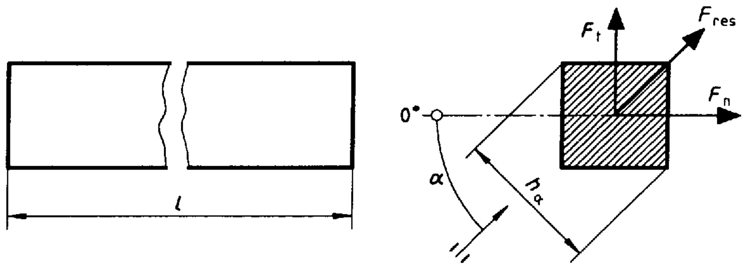
Reduction factor k_{red} for members of finite slenderness (in general, use full length not panel length)

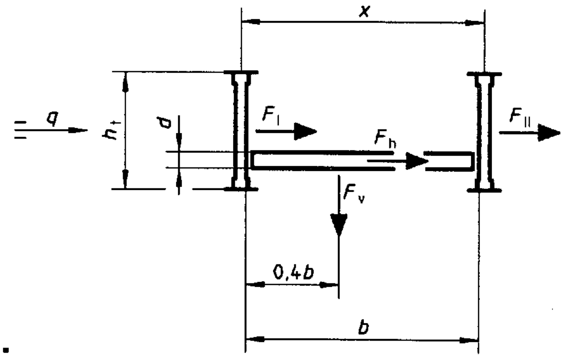
l/h_α	5	10	20	35	50	100	∞
k_{red}	0,60	0,65	0,75	0,85	0,90	0,95	1

For slenderness, h_α is to be used:



Length of member, l
Area, $A = h \cdot l$
For wind normal to axis of member:
Normal force $F_n = k_{red} \cdot C_{n,\infty} \cdot q \cdot C_{dyn} \cdot C_{exp} \cdot A$
Tangential force $F_t = k_{red} \cdot C_{t,\infty} \cdot q \cdot C_{dyn} \cdot C_{exp} \cdot A$

Figure D.10 — Structural members, single and assembled sections



a) **Case I — Without vehicles**

l_B = length of bridge

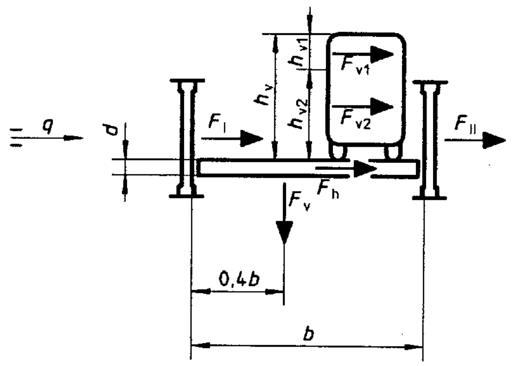
k_{red}, $C_{n,\infty}$, A_s, k_x from figures D.13 and D.14.

Force on windward girder $F_I = k_{red} \cdot C_{n,\infty} \cdot q \cdot C_{dyn} \cdot C_{exp} \cdot A_s$

Force on leeward girder $F_{II} = k_{red} \cdot C_{n,\infty} \cdot k_x q \cdot C_{dyn} \cdot C_{exp} \cdot A_s$

Horizontal force on deck: $F_h = 1{,}0 \cdot q \cdot C_{dyn} \cdot C_{exp} \cdot d \cdot l_B$

Vertical force on deck: $F_v = 0{,}6 \cdot q \cdot C_{dyn} \cdot C_{exp} \cdot b \cdot l_B$



b) **Case II — With vehicles**

l_v = length of vehicle

$A_1 = h_{v_1} \cdot l_v$

$A_2 = h_{v_2} \cdot l_v$

Force on windward girder $F_I = k_{red} \cdot C_{n,\infty} \cdot q \cdot C_{dyn} \cdot C_{exp} \cdot A_s$

Force on leeward girder $F_{II} = k_{red} \cdot C_{n,\infty} \cdot k_x q \cdot C_{dyn} \cdot C_{exp} \cdot A_s$

Horizontal force on deck: $F_h = 1{,}2 \cdot q \cdot C_{dyn} \cdot C_{exp} \cdot d \cdot l_B$

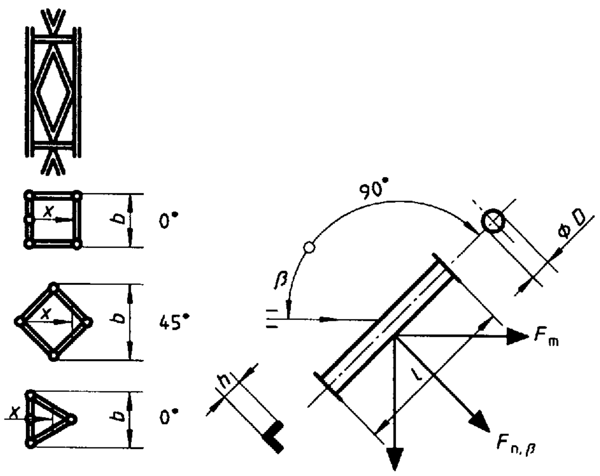
Vertical force on deck: $F_v = 0{,}8 \cdot q \cdot C_{dyn} \cdot C_{exp} \cdot b \cdot l_B$

Traffic load: $F_{v_1} = C_n \cdot q \cdot C_{dyn} \cdot C_{exp} \cdot A_1$

$F_{v_2} = C_n \cdot 2/3q \cdot C_{dyn} \cdot C_{exp} \cdot A_2$

Type of bridge traffic	h_v	C_n
Railway vehicle	3,8 m	1,5
Highway vehicle	3 m	1,2
Pedestrian	1,7 m	1

Figure D.11 — Truss and plate girder bridges



$A_s/A \leqslant 0,3$
$A = D \cdot l$ or $h \cdot l$
l = true length of member
β = angle between wind direction and the normal to member axis
k_x is a function of A_s/A and x/b

Total force in wind direction, $F = \sum F_m$

F_m = Force on member

$F_m = k_{red} \cdot C_{\infty,\beta} \cdot q \cdot C_{dyn} \cdot C_{exp} \cdot A\cos\beta$

For a shielded member

$F_m = k_{red} \cdot C_{\infty,\beta} \cdot k_x q \cdot C_{dyn} \cdot C_{exp} \cdot A\cos\beta$

For sharp-edged members

$C_{\infty,\beta} = k_\beta \cdot C_{n,\infty}$ and $k_\beta \cdot C_{t,\infty}$

See figure D.10 for $C_{n,\infty}$ and $C_{t,\infty}$ values

β	Sharp-edged members			Round members, smooth and rough surfaces $D\sqrt{qC_{exp}} < 0,167$			Round members, moderately smooth surfaces $D\sqrt{qC_{exp}} > 0,167$		
	k_β	k_{red}	k_x	$C_{\infty,\beta}$	k_{red}	k_x	$C_{\infty,\beta}$	k_{red}	k_x
0°	1	See figure D.10	See figure D.14	1,2	See figure D.10	See figure D.14	0,6	0,9 for $l/D = 25$	0,95
15°	0,98			1,16			0,58		
30°	0,93			1,04			0,53		
45°	0,88			0,85			0,42		
60°	0,8			0,6			0,28		

Figure D.12 — Three-dimensional trusses

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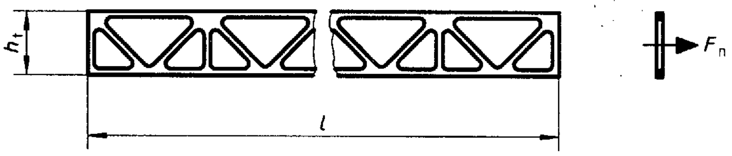
A_s = cross-section area

$A = h_t \cdot l$

A_s/A = solidity ratio

For wind normal to surface of area A:

Normal force $F_n = k_{red} \cdot C_{n,\infty} \cdot q \cdot C_{dyn} \cdot C_{exp} \cdot A_s$



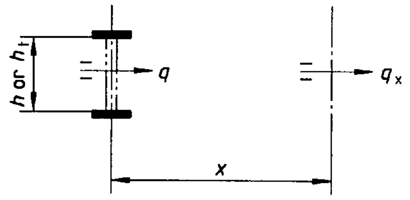
Force coefficient $C_{n,\infty}$ for an infinitely long truss, $0 \leqslant A_s/A \leqslant 1$

A_s/A	0	0,1	0,15	0,2	0,3 to 0,8	0,95	1
$C_{n,\infty}$	2	1,9	1,6	1,7	1,6	1,8	2

Reduction factor k_{red} for trusses of finite length and slenderness

l/h_t \ A_s/A	0,25	0,5	0,9	0,95	1
5	0,96	0,91	0,87	0,77	0,6
20	0,98	0,97	0,94	0,89	0,75
50	0,99	0,98	0,97	0,95	0,9
∞	1	1	1	1	1

Figure D.13 — Plane trusses made from sharp-edged sections



Shielding factor, k_x

x/h \ A_s/A	0,1	0,2	0,3	0,4	0,5	0,6	0,8	1
0,5	0,93	0,75	0,56	0,38	0,19	0	0	0
1	0,99	0,81	0,65	0,48	0,32	0,15	0,15	0,15
2	1	0,87	0,73	0,59	0,44	0,3	0,3	0,3
4	1	0,9	0,78	0,65	0,52	0,4	0,4	0,4
6	1	0,93	0,83	0,72	0,61	0,5	0,5	0,5

Figure D.14 — Shielding factors

Annex E
(informative)

Dynamic response factor, C_{dyn}

E.1 General remarks

This annex presents procedures which are recommended for determining the dynamic response factor referred to in clauses 5 and 9 of this International Standard. This factor, C_{dyn}, is defined as the ratio of the maximum effect of the loading to the mean effect of the loading incorporating the reference velocity pressure. It takes into account the dynamic (i.e. fluctuating with time) action of

— random wind gusts acting for short durations over all or part of the structure,

— fluctuating pressures induced by the wake of the structure, including vortex shedding forces, and

— fluctuating forces induced by the motion of the structure itself due to wind.

These forces act on the external surfaces of the structure as a whole or on cladding components and may also affect internal surfaces. They may act longitudinally, laterally or torsionally and may be amplified by resonance of the structure at one or other of its natural frequencies.

All structures are affected to some degree by these forces. The total response may be considered as a superposition of a "background" component, which acts quasi-statically without any structural dynamic magnification, and a "resonant" component due to excitation close to a natural frequency. For the majority of structures the resonant component is small and the dynamic factor can be simplified by considering the background component only and by using normal static methods. For structures which are particularly tall or long, slender, lightweight, flexible or lightly damped, the resonant component may be dominant.

Criteria are suggested for when these dynamic effects may be significant. The majority of structures can be treated using the simplified procedures given in annex A.

A general expression for the maximum or peak loading effect, W_p, is

$$W_p = W_m + g_w \sigma_w \quad \text{... (E.1)}$$

where

W_m is the mean loading effect;

σ_w is the root mean square (r.m.s) loading effect;

g_w is a statistical peak factor for the loading effect.

According to this expression a dynamic factor, equal to the ratio of the peak loading to the mean loading, can be identified as

$$C_{dyn} = 1 + (g_w \sigma_w / W_m), \text{ if } W_m \neq 0 \quad \text{... (E.2)}$$

The form of the fluctuating wind loading effect, σ_w, varies with the excitation, whether due to gusts, wake pressures or motion-induced forces. For a large class of smaller structures it is only necessary to deal with the additional loading due to gusts and simplified methods are therefore adequate. These are dealt with first. Criteria for the dynamic sensitivity are presented below.

The failure mechanism in foundations and footings (excluding the anchorages) are relatively insensitive to the dynamic component of the wind force. A nominal reduction factor of 0,7 is therefore allowed in estimating the failure load on these parts.

E.2 General response to gusts: rigid structures

E.2.1 Intensity of turbulence: flat and hilly terrain

The response of structures to gusts is proportional to the intensity of turbulence, I_u, which is the ratio of the root mean square fluctuating velocity to the mean.

Over flat terrain this is given approximately by

$$I_u \approx 1/\ln(h/z_0) \qquad \text{... (E.3)}$$

where

h is the height of the structure;

z_0 is the roughness length of terrain (see C.2 and figure C.1).

For representative open country conditions, z_0 = 0,03 m, and for structures of height of the order of 10 m, $I_u \approx 0{,}17$.

In hilly terrain, near the crest of hills and escarpments, the mean wind velocity may experience a speed-up effect without significantly affecting the amplitude of the turbulence. It is then necessary to replace I_u by a reduced value of the turbulence intensity, I_u*, given by

$$I_u^* = I_u\sqrt{C_{exp}/C_{exp,\,mod}} \qquad \text{... (E.4)}$$

where $C_{ex,\,mod}$ is the modified exposure factor in hilly terrain (see C.4 and equation (C.4).

E.2.2 Small rigid structures

For small structures 10 m high or less, and having a relatively high rigidity we find

$$\sigma_W/W_m \approx 2I_u \qquad \text{... (E.5)}$$

The peak factor, g_W, for external pressure is approximately 4 for local cladding components and 3 for structural components. In addition, a reduction factor of 0,7 is allowed for footings and foundations. This leads to a simplified set of dynamic gust factors for open country, as follows:

$$C_{dyn} = 1 + 2g_W I_u \qquad \text{... (E.6)}$$

$C_{dyn} \approx 2{,}5$ for cladding elements

$C_{dyn} \approx 2{,}0$ for structural components

$C_{dyn} \approx 1{,}4$ for foundations and footings (excluding anchorage).

These values have been proposed for use with the simplified method in annex A.

For some structures, peak pressure coefficients have been determined directly from wind-tunnel tests, and composite values of ($C_{fig}C_{dyn}$) are obtained incorporating the aerodynamic shape factors. For low buildings with gable roofs, such values are given in annex A.

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E.2.3 Large rigid structures

For the overall response of large as well as small structures which are relatively rigid and do not exhibit strong resonance characteristics, the fluctuating response can be written as

$$\sigma_w / W_m = 2 I_u B \qquad \text{... (E.7)}$$

where B is a background response factor which depends on size. This leads to

$$C_{dyn} = 1 + 2 g_w I_u B \qquad \text{... (E.8)}$$

where g_w can vary between 2,5 and 4 depending primarily on the size of the structure and on the averaging period. A value of 3 is appropriate for general use.

Numerical values of B for the calculation of wind loads for rigid structures are given in figure E.1.

E.3 Flexible or dynamically sensitive structures

E.3.1 Response to gusts in the direction of the wind

For more flexible structures liable to resonant amplification, the fluctuation response can be written as

$$\sigma_w / W_m = 2 I_u \sqrt{B^2 + R^2} \qquad \text{... (E.9)}$$

In this equation, R represents the resonant response and the other terms are defined in E.1 and E.2. If $\sqrt{B^2 + R^2}$ is rewritten as $B\sqrt{1 + (R/B)^2}$, the term $\sqrt{1 + (R/B)^2}$ then represents a resonant magnification factor multiplying the background response factor B, and is a useful indicator of the dynamic sensitivity. According to equation (E.2) the dynamic response factor may then be expressed as

$$C_{dyn} = 1 + 2 g_w I_u B \sqrt{1 + (R/B)^2} \qquad \text{... (E.10)}$$

A more detailed expression for g_w, for use with this equation, is

$$g_w = \sqrt{2 \ln(\nu T)} + 0{,}58 \big/ \sqrt{2 \ln(\nu T)} \qquad \text{... (E.11)}$$

where

ν is the cycling rate of the oscillation;

T is the averaging time for the reference velocity pressure (taken in this International Standard as 600 s).

An expression for νT is

$$\nu T = f_0 T (R/B) \big/ \sqrt{1 + (R/B)^2} \qquad \text{... (E.12)}$$

where f_0 is the natural frequency.

For tall structures cantilevered at the base, such as tall buildings, chimneys and towers, the quantity R/B should be determined from the following:

for $b/h > 0{,}25$

$$(R/B)^2 = (\pi/4)(S)(Q)^{4/3} / \zeta \qquad \text{... (E.13)}$$

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for $b/h < 0{,}25$

$$(R/B)^2 = (\pi/4)(S')(Q)^{5/6}/\zeta \qquad \text{... (E.14)}$$

where

S and S' are the spectral energy factors given in figure E.1;

Q is the squared reduced velocity;

ζ is the damping ratio.

The squared reduced velocity can be expressed either by

$$Q = \left[v_{hcr}/(f_0 h)\right]^2 \qquad \text{... (E.15)}$$

where

v_{hcr} is the mean wind speed at the top of the structure ($z = h$);

f_0 is the natural frequency;

or by the approximation

$$Q \approx (8\pi^2/C_D)(d/h)(\rho_{bldg}/\rho_{air})(\bar{\delta}/h) \qquad \text{... (E.16)}$$

where (see figure E.1)

d/h is the slenderness;

$\bar{\delta}/h$ the ratio of the mean deflection under the mean wind load to the height (i.e. with $C_{dyn} = 1$);

ρ_{bldg}/ρ_{air} is the ratio of the average density of the envelope of the upper third of the building's superstructure to the air density (1,2 kg/m^3);

C_D is the drag coefficient.

The damping ratio, ζ, is the total damping expressed as a fraction of the critical damping ratio. It can be equated to the structural damping, ζ_{str}, in many cases. Representative values of structural damping are given in table E.1. (It should be noted that there is high variability in values of damping found in structures and a trend for damping values to increase with amplitude).

Table E.1 — Representative values of structural damping ratio, ζ_{str}

Type of structure	Material	
	Steel	Concrete
Tall buildings	0,01	0,015
Chimneys	0,002[1)] 0,005[2)]	0,01
Lattice towers	0,01	—

1) Unlined, all welded.
2) Lined.
NOTE — The damping ratio is equal to the logarithmic decrement of damping divided by 2π.

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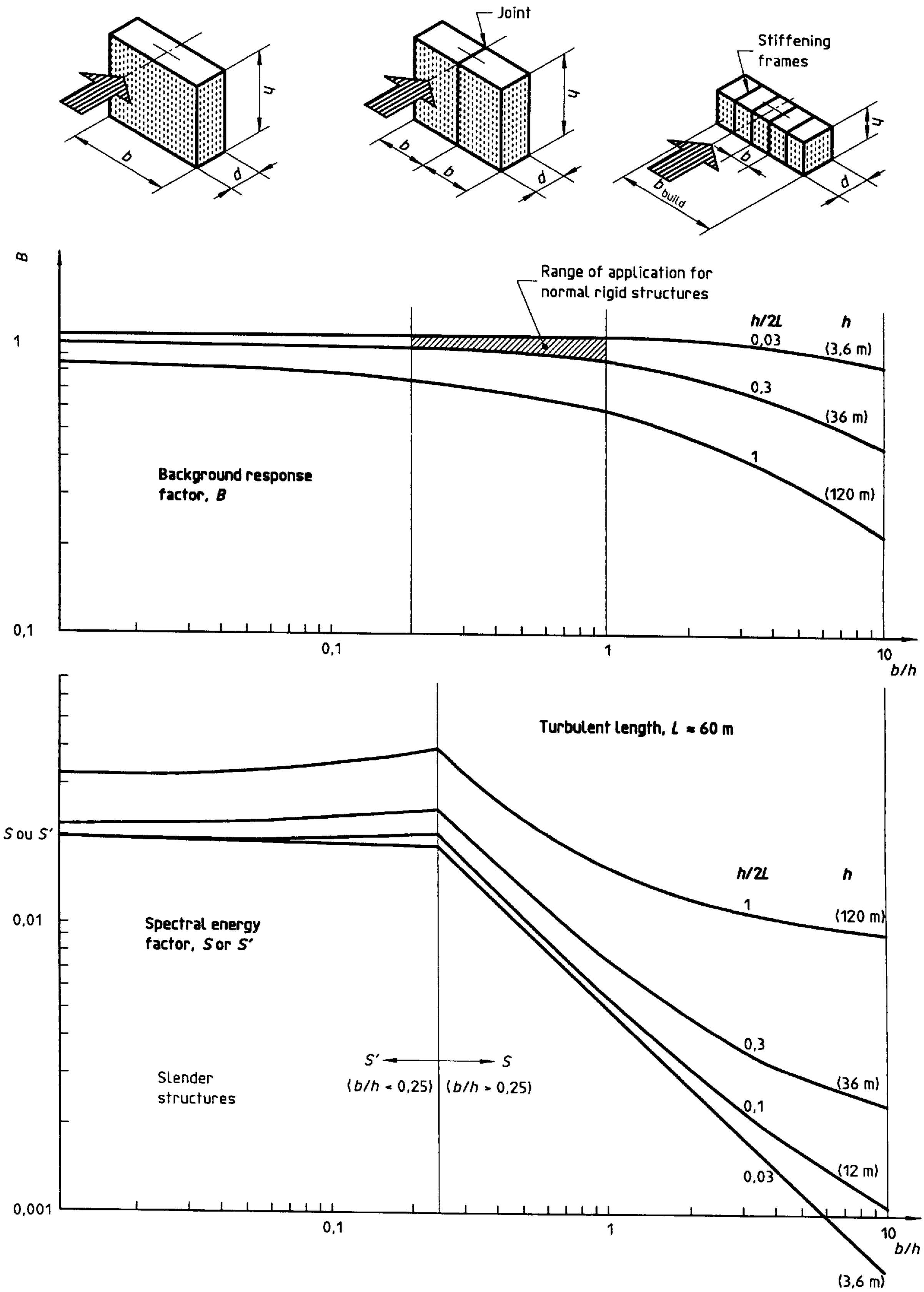

Figure E.1 — Dynamic response factor parameters

E.3.2 Peak accelerations

The peak acceleration a_p can be found from the expression

$$a_p = 2g_w \cdot I_u B(R/B)\, 4\pi^2 f_0^2 \bar{\delta} \qquad \text{... (E.17)}$$

where all the quantities are as before.

Acceleration may be unacceptable in tall buildings when the peak acceleration exceeds approximately 1,5 % to 2,5 % of the acceleration due to gravity every 10 years. The lower figure is likely to be more appropriate for apartment buildings.

E.3.3 Criterion for resonance

Equation (E.9) suggests that for along-wind excitation of buildings a criterion for assessment of sensitivity to resonance is

$$(R/B)^2 < \text{constant} \qquad \text{... (E.18)}$$

When R/B is evaluated from equations (E.13) to (E.16), equation (E.18) is useful in controlling the mean deflection ratio $\bar{\delta}/h$ and the acceleration. A suitable value for the constant is 0,5.

E.3.4 Crosswind, torsional and other responses due to gusts

Gusts or turbulence may also excite other responses due to the local changes of wind speed and direction. Where necessary these should also be taken into account. Generally speaking the crosswind action of gusts is similar to the along-wind action, but relative to the area affected which is somewhat smaller in magnitude. Crosswind mean loading effects are likewise smaller unless the structure is extremely unsymmetrical in shape. (The crosswind action of vortex shedding is often more important and is discussed in the following section.)

Torsional loadings due to gusts can under certain circumstances be extremely serious. This is particularly the case where the torsional frequencies are low, or there is non-alignment of the geometric (or aerodynamic loading) centre of the structural cross-section, the centre of mass and the centre of twist. (See also D.13.)

Unbalanced or asymmetric loading effects on overhang cantilever structures or flexible roofs, for example, can also be caused by gusts.

E.3.5 Aerodynamic damping

Flexible structures vibrating in the wind experience the effects of aerodynamic as well as structural damping. For slender structures, the aerodynamic damping ratio can be expressed as

$$\zeta_{aer} = \left(\frac{\rho_{air} d^2}{m_i}\right)\left(\frac{v_{hcr}}{f_0 d}\right) C_{aer} \qquad \text{... (E.19)}$$

in which d and m_i are representative width and mass per unit length of the cross-section. The aerodynamic damping coefficient C_{aer} is a function of the geometry and the reduced velocity ($v_h/f_0 d$). At large enough values of the reduced velocity (say greater than 10), the value of C_{aer} usually approaches a quasi-steady value in the approximate range ± 0,5.

As a guide it is useful to determine the magnitude of the product of the first two terms on the right-hand side; if this yields a value greater than approximately 0,01, aerodynamic damping is likely to be of comparable magnitude to the structural damping.

It should be noted that the aerodynamic damping can be negative. If it is, and if it is large enough that the sum of the aerodynamic damping and structural damping is less than zero, instability will result and lead to steadily increasing amplitude. Negative aerodynamic damping is encountered with many shapes including rectangular building shapes

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and some bridge cross-sections. It is also encountered at vortex shedding frequencies and is responsible for the large amplitude motion occasionally associated with this.

Equation (E.19) is useful for determining only approximate magnitudes.

For along-wind aerodynamic damping, the value of C_{aer} in equation (E.19) is approximately $C_D/(4\pi)$ where C_D is the drag coefficient (shape factor for the along-wind direction).

E.4 Wake-induced fluctuating pressures (vortex shedding)

Slender free-standing cylindrical structures, such as chimneys, observation towers and in some cases high-rise buildings, should be designed to resist the dynamic effect of vortex shedding. When the wind blows across a slender prismatic or cylindrical body, vortices are shed alternately from one side and then the other giving rise to fluctuating forces acting along the length of the body at right angles to the wind direction and the axis of the body. There is, in addition, the tendency for the aerodynamic damping to become negative. A structure may be considered slender in this context if the ratio of the height to the diameter exceeds 6.

The critical wind velocity, v_{hcr}, at the top of a structure when the frequency of vortex shedding equals the natural frequency, f_0, of the structure is given by

$$v_{hcr} = f_0 D / Sr \qquad \text{... (E.20)}$$

where

Sr is the Strouhal Number;

D is the diameter.

For circular and near-circular cylinders,

$$Sr \approx 0{,}18 \text{ for } v_{hcr}D < 3{,}3 \text{ m}^2/\text{s}$$

$$Sr \approx 0{,}2 \text{ for } v_{hcr}D > 3{,}3 \text{ m}^2/\text{s} \qquad \text{... (E.21)}$$

NOTE — The product $v_{hcr}D$ is proportional to the Reynold's number, Re, of the chimney, that is $Re = 6{,}7\ v_{hcr}D \times 10^4$.

The critical wind velocity v_{hcr} corresponds to a critical velocity pressure

$$q_{hcr} = \frac{1}{2} \rho_{air} v_{hcr}^2 \qquad \text{... (E.22)}$$

Three situations can arise in relation to vortex shedding:

— the critical wind velocity is much greater than the design wind velocity, in which case no further consideration is required;

— the aerodynamic damping of the chimney is negative and its magnitude is greater than the structural damping, in which case large amplitude motions will result;

— the aerodynamic damping is smaller than the structural damping and moderate amplitude motions will occur.

These three situations are discussed in more detail in a), b) and c).

a) Following the requirement in clause 10 of this International Standard, if the critical velocity $v_{hcr} > \sqrt{\gamma_w} \cdot v_{ref}$ (or $q_{hcr} > \gamma_w q_{ref}$), no further consideration need be given to vortex shedding. This is the first check necessary. If $v_{hcr} < \sqrt{\gamma_w} \cdot v_{ref}$, then the requirements of b) and c) apply.

b) At the critical wind velocity the aerodynamic damping for amplitudes limited to a small fraction of the diameter is negative, $v_h/(f_0 D) = Sr^{-1}$ and equation (E.19) can be written

$$\begin{aligned}\zeta_{aer} &= \frac{\rho_{air} D^2}{m_i}\frac{C_{aer}}{Sr} \\ &= -\frac{\rho_{air} D^2}{m_i} C_2\end{aligned} \qquad \text{... (E.23)}$$

where C_2 is a positive coefficient given below.

Both the mass per unit length, m_i, and the diameter, D, should be averaged over the top third of the chimney. If the structural damping (as defined in table E.1) exceeds the magnitude of the negative aerodynamic damping, i.e. $\zeta_{str} > (\rho_{air}D^2/m_i)C_2$, the motion will be stable and the requirements of c) should be considered. If $\zeta_{str} < (\rho_{air}D^2/m_i)C_2$, the motion will be unstable and large amplitudes up to the value of D may result, with the possibility of fatigue failure. Special treatment is then required either by referral to experts, special codes (e.g. on steel stacks) or special investigations.

It should be noted that the quantity $4\pi\zeta_{str}m_i/(\rho_{air}D^2)$ is sometimes referred to as the Scruton number, Sc. The criterion $Sc < 10$ can be used to indicate the onset of large amplitude motions.

c) If the motion is stable, i.e. $\zeta_{str} > (\rho_{air}D^2/m_i)C_2$, the vortex-excited amplitude y_0 can be estimated using the formula

$$\frac{y_0}{D} = \frac{C_3\left(\rho_{air}D^2/m_i\right)}{(h/D)^{1/2}\left[\zeta_{str} - \left(\rho_{air}D^2/m_i\right)C_2\right]^{1/2}} \qquad \text{... (E.24)}$$

where C_2 and C_3 are given below.

The wind force per unit length can then be calculated from

$$W_L = 4\pi^2 f_0^2 m_i \phi_i y_0 \qquad \text{... (E.25)}$$

where ϕ_i is the ratio of the dynamic deflection of the structure at point i, to the maximum deflection (at the top). The value of y_0 is given by equation (E.24).

Alternatively, the dynamic effects of vortex shedding from a cylindrical structure can be approximated by a static force acting over the top third. The equivalent static wind force per unit height, W_L, is given by

$$W_L = q_{hcr} D\left\{C_1(h/D)^{-1/2}\left[\zeta_{str} - \left(\rho_{air}D^2/m_i\right)C_2\right]^{-1/2}\right\} \qquad \text{... (E.26)}$$

where ζ_{str} is the structural damping ratio (as defined in table E.1). The value of q_{hcr} is given by equation (E.22) and D and m_i are the average diameter and mass per unit length over the top third of the structure.

NOTE — In this case the quantity in braces {} is equivalent to $(C_{fig}C_{dyn})$, and C_{exp} is incorporated in q_{hcr}.

For most circular chimneys:

$C_1 = 3$ for $(h/D) > 16$

or

$C_1 = \frac{3\sqrt{h/D}}{4}$ for $(h/D) < 16$

$C_2 = 0{,}6$

$C_3 = 1$

At low critical wind velocities the atmosphere near the surface may be stable and produce very low turbulence levels, and in such cases vortex-induced motions are significantly increased, particularly for very slender structures. For $v_{hcr} < 10$ m/s and $(h/D) > 12$ then

$C_1 = 6$

$C_2 = 1{,}2$

$C_3 = 2$

For tapered structures some reduction in the vortex shedding forces can be made if the variation in the diameter over the top third is greater than 10 % of the average diameter of the top third. The effective static load then need be applied only over that part of the structure over which the diameter is within 10 % of the average for that part.

For tapered structures with a diameter variation exceeding 10 % over the top third

$C_1 = 3$

$C_2 = 0{,}6$

$C_3 = 1{,}2$

and no increase in these coefficients is required for low values of v_{hcr}.

The recommendations of this section apply to free-standing structures vibrating in the fundamental mode. For other mode shapes a dynamic analysis would be appropriate although equation (E.20) may be used to determine the critical velocity, and the application of equation (E.24) will yield a rough estimate of the effects of vortex shedding. Slender structures with cross-sections other than circular may also give rise to vortex shedding, but data are limited and, in addition, other forms of crosswind motion may develop if the wind velocity, v_{hcr}, is greater than $7f_0b$, where b is the across-wind breadth of the structure. In such cases wind-tunnel tests provide the most satisfactory method of estimating the likely response.

E.5 Aeroelastic instability

The motion (or distortion) of a structure due to the wind loads can cause aeroelastic forces which depend, in part, on the velocity of the structure itself. These forces are called aerodynamic damping forces and can either oppose or assist the motion. If they oppose the motion they constitute positive aerodynamic damping; if they assist the motion, negative aerodynamic damping. The sum of the aerodynamic damping and the structural damping constitutes the total effective damping. The total resonant response of the structure is inversely related to the total damping.

As noted in E.3.5, if the aerodynamic damping is negative the total damping available is reduced, in some cases to zero. Under these circumstances the amplitudes of vibration become extremely large and the motion is described as unstable. The limitation of the amplitudes, if any, is defined by the "second-order effects" of the system and flow. Generally these amplitudes are prohibitively large; under certain circumstances, however, with suitably flexible structures, the limiting amplitudes may be acceptable provided that fatigue is taken into account.

Aerodynamic damping forces will be generated whenever a structure is in motion through the flow. Negative aerodynamic damping forces can arise under a variety of circumstances. One of these, described as galloping, involves the transverse oscillation of a structure and is associated with a "negative slope" to the side force/angle of attack relationship. The necessary characteristics are exhibited both by common structural shapes and iced cables. Negative aerodynamic damping characteristics are also found at certain wind velocities in both lift and torsional motion of bridge decks. A particularly important situation is produced by the negative aerodynamic damping forces set up at the critical wind velocity at which the vortex-shedding frequency coincides with the natural frequency of the structure. The forces are sometimes referred to as "locked-in" forces rather than negative aerodynamic damping forces.

Other forms of instability can occur involving the coupling of several modes of vibration. These are described as "flutter". They are only likely to affect exceptionally light, flexible structures such as suspension bridges. In all these instances, the problem should be given special treatment.

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Annex F
(informative)

Safety considerations

The following comments may be of assistance in assessing the safety of structures under wind loading.

Engineering quantities inevitably contain uncertainties. In the estimation of wind loading, the specified load will be multiplied by a load factor which is intended to take account of this uncertainty. The appropriate value of the load factor corresponding to a given risk level can be estimated using reliability theory if statistical properties of the variables are known.

Precise estimates of these statistics for wind loading are difficult to obtain. Nevertheless, approximate estimates of the ratios of the expected (mean) values to specified values can be given as well as the coefficients of variations (see table F.1).

In the case of aerodynamic instability, some protection is needed to ensure that the structure does not become unstable at a wind velocity marginally higher than the design wind speed. In principle, this can be done using reliability theory but it may offer difficulties. In the absence of an alternative, a relatively simple rule based on the load factor is suggested

Table F.1 — Uncertainty in engineering quantities used in wind loading calculations

Quantity	Ratio of expected value to specified value	Coefficient of variation
q (once-in-50 year value)	0,8	0,2 to 0,3
C_{exp}	0,8	0,1 to 0,2
C_{fig}	0,9	0,1 to 0,2
C_{dyn}	1	0,1 to 0,2
ζ_{str}	1	0,4 to 0,5

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