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Eurocode 1 — Actions on structures — Part 1‑4: Wind actions

Eurocode 1 — Einwirkungen auf Tragwerke — Teil 1‑4: Windlasten

Eurocode 1 — Actions sur les structures — Partie 1‑4: Actions du vent

ICS:

Contents Page

[European foreword 6](#_Toc151109953)

[0 Introduction 7](#_Toc151109954)

[1 Scope 11](#_Toc151109955)

[1.1 Scope of prEN 1991‑1‑4 11](#_Toc151109956)

[1.2 Assumptions 11](#_Toc151109957)

[2 Normative references 11](#_Toc151109958)

[3 Terms, definitions and symbols 12](#_Toc151109959)

[3.1 Terms and definitions 12](#_Toc151109960)

[3.2 Symbols 13](#_Toc151109961)

[4 Design situations 18](#_Toc151109962)

[5 Modelling of wind actions 19](#_Toc151109963)

[5.1 Representations of wind actions 19](#_Toc151109964)

[5.2 Classification of wind actions 19](#_Toc151109965)

[5.3 Characteristic values 19](#_Toc151109966)

[5.4 Loading models 19](#_Toc151109967)

[5.5 Design assisted by testing and measurements 23](#_Toc151109968)

[6 Wind velocity and velocity pressure 23](#_Toc151109969)

[6.1 Basis for calculation 23](#_Toc151109970)

[6.2 Basic values 24](#_Toc151109971)

[6.3 Mean wind velocity and pressure 25](#_Toc151109972)

[6.4 Wind turbulence 29](#_Toc151109973)

[6.5 Peak wind velocity and velocity pressure 30](#_Toc151109974)

[7 Wind actions 31](#_Toc151109975)

[7.1 General 31](#_Toc151109976)

[7.2 Choice of aerodynamic coefficient 32](#_Toc151109977)

[7.3 Wind pressure on surfaces 32](#_Toc151109978)

[7.4 Net pressure on surfaces 33](#_Toc151109979)

[7.5 Wind forces 33](#_Toc151109980)

[8 Structural factor 35](#_Toc151109981)

[8.1 General 35](#_Toc151109982)

[8.2 Approximate determination of 35](#_Toc151109983)

[8.3 Serviceability assessments 38](#_Toc151109984)

[9 Across-wind and torsional actions on buildings 38](#_Toc151109985)

[10 Aeroelastic phenomena 38](#_Toc151109986)

[10.1 General 38](#_Toc151109987)

[10.2 Basis for calculation 38](#_Toc151109988)

[10.3 Galloping 41](#_Toc151109989)

[10.4 Divergence and flutter 41](#_Toc151109990)

[10.5 Wake buffeting 41](#_Toc151109991)

[Annex A (informative) This page is left blank intentionally 42](#_Toc151109992)

[A.1 Editorial Note 42](#_Toc151109993)

[Annex B (informative) Terrain effects 43](#_Toc151109994)

[B.1 Use of this annex 43](#_Toc151109995)

[B.2 Scope and field of application 43](#_Toc151109996)

[B.3 Illustrations of the upper roughness of each terrain category 43](#_Toc151109997)

[B.4 Transition between terrain categories 0, I, II, III and IV 44](#_Toc151109998)

[B.5 Orography coefficients 46](#_Toc151109999)

[B.6 Neighbouring structures 51](#_Toc151110000)

[B.7 Displacement height 52](#_Toc151110001)

[B.8 Alternative wind model 53](#_Toc151110002)

[Annex C (normative) Pressure coefficients for pressures on surface 56](#_Toc151110003)

[C.1 Use of this annex 56](#_Toc151110004)

[C.2 Scope and field of application 56](#_Toc151110005)

[C.3 Pressure and force coefficients 56](#_Toc151110006)

[C.4 Pressure coefficients for rectangular plan buildings 57](#_Toc151110007)

[C.5 Pressure coefficients for irregular buildings 84](#_Toc151110008)

[C.6 Pressure coefficients for circular structures 89](#_Toc151110009)

[C.7 Internal pressures 101](#_Toc151110010)

[Annex D (normative) Net pressure and force coefficients for walls, roofs and skins 104](#_Toc151110011)

[D.1 Use of this annex 104](#_Toc151110012)

[D.2 Scope and field of application 104](#_Toc151110013)

[D.3 Net pressure and force coefficients for canopy roofs, porches and balconies 104](#_Toc151110014)

[D.4 Net pressure coefficients for free-standing walls, parapets, fences and signboards 115](#_Toc151110015)

[Annex E (normative) Force coefficients for structures and structural members 121](#_Toc151110016)

[E.1 Use of this annex 121](#_Toc151110017)

[E.2 Scope and field of application 121](#_Toc151110018)

[E.3 General 121](#_Toc151110019)

[E.4 Force coefficients for spheres 130](#_Toc151110020)

[E.5 Force coefficients for square and triangular lattice structures and scaffoldings 132](#_Toc151110021)

[E.6 Force coefficients for flags 141](#_Toc151110022)

[E.7 Force coefficients for iced structures 142](#_Toc151110023)

[E.8 Force coefficients for bridge decks 146](#_Toc151110024)

[E.9 Friction coefficients 155](#_Toc151110025)

[Annex F (informative) Procedure for along-wind dynamic response 157](#_Toc151110026)

[F.1 Use of this annex 157](#_Toc151110027)

[F.2 Scope and field of application 157](#_Toc151110028)

[F.3 Along-wind dynamic response 157](#_Toc151110029)

[F.4 Along-wind turbulence 157](#_Toc151110030)

[F.5 Constant sign mode shapes 159](#_Toc151110031)

[F.6 Background response factor 166](#_Toc151110032)

[F.7 Resonance response factor 168](#_Toc151110033)

[F.8 Peak factor for resonant response 170](#_Toc151110034)

[F.9 Non-constant sign mode shapes — Calculation of equivalent static wind force 171](#_Toc151110035)

[F.10 Number of loads for dynamic response 175](#_Toc151110036)

[Annex G (informative) Procedure for across-wind and torsional actions on susceptible buildings 177](#_Toc151110037)

[G.1 Use of this annex 177](#_Toc151110038)

[G.2 Scope and field of application 177](#_Toc151110039)

[G.3 General 177](#_Toc151110040)

[G.4 Detailed procedure for across-wind actions 178](#_Toc151110041)

[G.5 Detailed procedure for torsional actions 182](#_Toc151110042)

[G.6 Simplified procedure for across-wind and torsional actions for square plan buildings 185](#_Toc151110043)

[G.7 Across-wind and torsional accelerations 187](#_Toc151110044)

[G.8 Combination of actions and action effects 188](#_Toc151110045)

[Annex H (informative) Procedure for across-wind dynamic and aeroelastic response of slender structures 190](#_Toc151110046)

[H.1 Use of this annex 190](#_Toc151110047)

[H.2 Scope and field of application 190](#_Toc151110048)

[H.3 General 190](#_Toc151110049)

[H.4 Across-wind dynamic response 191](#_Toc151110050)

[H.5 Vortex shedding 198](#_Toc151110051)

[H.6 Galloping 210](#_Toc151110052)

[H.7 Divergence and flutter 214](#_Toc151110053)

[Annex I (informative) Dynamic characteristics of structures with linear elastic behaviour 219](#_Toc151110054)

[I.1 Use of this annex 219](#_Toc151110055)

[I.2 Scope and field of application 219](#_Toc151110056)

[I.3 General 219](#_Toc151110057)

[I.4 Fundamental frequency 219](#_Toc151110058)

[I.5 Fundamental mode shape 226](#_Toc151110059)

[I.6 Equivalent mass 229](#_Toc151110060)

[I.7 Logarithmic decrement of damping 229](#_Toc151110061)

[Annex J (informative) Response of steel lattice towers and guyed masts 232](#_Toc151110062)

[J.1 Use of this annex 232](#_Toc151110063)

[J.2 Scope and field of application 232](#_Toc151110064)

[J.3 General 232](#_Toc151110065)

[J.4 Response of lattice towers 232](#_Toc151110066)

[J.5 Response of guyed masts 237](#_Toc151110067)

[Annex K (informative) Guidance on derivation of design parameters from wind tunnel tests and numerical simulations 247](#_Toc151110068)

[K.1 Use of this annex 247](#_Toc151110069)

[K.2 Scope and field of application 247](#_Toc151110070)

[K.3 General 247](#_Toc151110071)

[K.4 Derivation of design parameters from wind tunnel tests 248](#_Toc151110072)

[K.5 Derivation of design parameters from numerical simulations 256](#_Toc151110073)

[Annex L (informative) Guidance on derivation of wind speeds from measurements at meteorological stations 261](#_Toc151110074)

[L.1 Use of this annex 261](#_Toc151110075)

[L.2 Scope and field of application 261](#_Toc151110076)

[L.3 Wind Speed Records 261](#_Toc151110077)

[L.4 Extreme Value or Parent Population Analysis 262](#_Toc151110078)

[Annex M (informative) Guidance on probabilistic description of wind actions 263](#_Toc151110079)

[M.1 Use of this annex 263](#_Toc151110080)

[M.2 Scope and field of application 263](#_Toc151110081)

[M.3 Probabilistic variables 263](#_Toc151110082)

[M.4 Calibration of the values of the terms on basis of their statistical distribution 264](#_Toc151110083)

[Bibliography 265](#_Toc151110084)

European foreword

This document (prEN 1991‑1‑4:2024) has been prepared by Technical Committee CEN/TC 250 “Structural Eurocode”, the secretariat of which is held by BSI. CEN/TC 250 is responsible for all Structural Eurocodes and has been assigned responsibility for structural and geotechnical design matters by CEN.

This document is currently submitted to the CEN Enquiry.

This document will supersede EN 1991‑1‑4:2005 and its amendments and corrigenda.

The first generation of EN Eurocodes was published between 2002 and 2007. This document forms part of the second generation of the Eurocodes, which have been prepared under Mandate M/515 issued to CEN by the European Commission and the European Free Trade Association.

The Eurocodes have been drafted to be used in conjunction with relevant execution, material, product and test standards, and to identify requirements for execution, materials, products and testing that are relied upon by the Eurocodes.

The Eurocodes recognize the responsibility of each Member State and have safeguarded their right to determine values related to regulatory safety matters at national level through the use of National Annexes.

0 Introduction

**0.1 Introduction to the Eurocodes**

The structural Eurocodes comprise the following standards generally consisting of a number of parts:

* EN 1990, Eurocode — Basis of structural and geotechnical design
* EN 1991, Eurocode 1 — Actions on structures
* EN 1992, Eurocode 2 — Design of concrete structures
* EN 1993, Eurocode 3 — Design of steel structures
* EN 1994, Eurocode 4 — Design of composite steel and concrete structure
* EN 1995, Eurocode 5 — Design of timber structures
* EN 1996, Eurocode 6 — Design of masonry structures
* EN 1997, Eurocode 7 — Geotechnical design
* EN 1998, Eurocode 8 — Design of structures for earthquake resistance
* EN 1999, Eurocode 9 — Design of aluminium structures
* New Eurocodes under development, e.g. Eurocode for design of structural glass

The Eurocodes are intended for use by designers, clients, manufacturers, constructors, relevant authorities (in exercising their duties in accordance with national or international regulations), educators, software developers, and committees drafting standards for related product, testing and execution standards.

NOTE Some aspects of design are most appropriately specified by relevant authorities or, where not specified, can be agreed on a project-specific basis between relevant parties such as designers and clients. The Eurocodes identify such aspects making explicit reference to relevant authorities and relevant parties.

**0.2 Introduction to EN 1991 (all parts)**

EN 1991 specifies actions for the structural design of buildings, bridges and other civil engineering works, or parts thereof, including temporary structures, in conjunction with EN 1990 and the other Eurocodes.

EN 1991 does not cover the specific requirements of actions for seismic design. Provisions related to such requirements are given in EN 1998 (all parts), which complement and are consistent with EN 1991.

EN 1991 is also applicable to existing structures for their:

* structural assessment,
* strengthening or repair,
* change of use.

NOTE In these cases, additional or amended provisions can be necessary.

EN 1991 is applicable for the design of structures where materials or actions outside the scope of the other Eurocodes are involved.

NOTE In this case, additional or amended provisions can be necessary.

EN 1991 is subdivided in various parts:

* EN 1991‑1‑1, *Eurocode 1 — Actions on structures — Part 1‑1: Specific weight of materials, self-weight of construction works and imposed loads for buildings*
* EN 1991‑1‑2, *Eurocode 1 — Actions on structures — Part 1‑2: Actions on structures exposed to fire*
* EN 1991‑1‑3, *Eurocode 1 — Actions on structures — Part 1‑3: Snow Loads*
* EN 1991‑1‑4, *Eurocode 1 — Actions on structures — Part 1‑4: Wind Actions*
* EN 1991‑1‑5, *Eurocode 1 — Actions on structures — Part 1‑5: Thermal Actions*
* EN 1991‑1‑6, *Eurocode 1 — Actions on structures — Part 1‑6: Actions during execution*
* EN 1991‑1‑7, *Eurocode 1 — Actions on structures — Part 1‑7: Accidental actions*
* EN 1991‑1‑8, *Eurocode 1 — Actions on structures — Part 1‑8: Actions from waves and currents on coastal structures*
* EN 1991‑1‑9, *Eurocode 1 — Actions on structures — Part 1-9: Atmospheric icing*
* EN 1991‑2, *Eurocode 1 — Actions on structures — Part 2: Traffic loads on bridges and other civil engineering works*
* EN 1991‑3, *Eurocode 1 — Actions on structures — Part 3: Actions induced by cranes and machines*
* EN 1991‑4, *Eurocode 1 — Actions on structures — Part 4: Silos and tanks*

**0.3 Introduction to prEN 1991‑1‑4**

prEN 1991‑1‑4 gives design guidance and actions for the structural design of buildings and civil engineering works for wind.

prEN 1991‑1‑4 is intended to be used with EN 1990, the other Parts of EN 1991 and EN 1992 to EN 1999 for the design of structures.

**0.4 Verbal forms used in the Eurocodes**

The verb “shall” expresses a requirement strictly to be followed and from which no deviation is permitted in order to comply with the Eurocodes.

The verb “should” expresses a highly recommended choice or course of action. Subject to national regulation and/or any relevant contractual provisions, alternative approaches could be used/adopted where technically justified.

The verb “may” expresses a course of action permissible within the limits of the Eurocodes.

The verb “can” expresses possibility and capability; it is used for statements of fact and clarification of concepts.

**0.5 National Annex for prEN 1991‑1‑4**

National choice is allowed by this standard where explicitly stated within notes. National choice includes the selection of values for Nationally Determined Parameters (NDPs).

The national standard implementing prEN 1991‑1‑4 can have a National Annex containing all national choices to be used for the design of buildings and civil engineering works to be constructed in the relevant country.

When no national choice is given, the default choice given in this standard is to be used.

When no national choice is made and no default choice is given in this standard, the choice can be specified by the relevant authority or, where not specified, agreed for a specific project by the relevant parties.

National choice is allowed in prEN 1991‑1‑4 through notes to the following clauses:

|  |  |  |  |
| --- | --- | --- | --- |
| 5.4(8) | 6.1(3) | 6.2(1) | 6.2(2) |
| 6.2(4) | 6.2(5) | 6.3.1(1) | 6.3.2(1) |
| 6.3.2(3) | 6.3.3(2) | 6.4(2) | 6.4(3) |
| 6.4(4) | 6.5(1) | 7.1(2) | 9(1) |
| B.1(1) | B.3(1) | B.4.1(2) | B.4.3(5) |
| B.5(5) | B.8.1(1) | B.8.2(1) | Table B.3 (NDP) |
| B.8.3(2) | C.3.1(1) | C.3.2(1) | C.4.1(4) |
| C.4.1(6) | C.4.2(6) | C.4.3(3) | Table C.3 (NDP) |
| C.4.4(3) | C.4.4(4) | C.4.5(3) | C.4.5(4) |
| C.4.6(3) | C.4.8(1) | C.4.9(2) | C.4.9(3) |
| C.5.1(2) | C.5.2(1) | C.5.3(1) | C.6.1.1(1) |
| C.6.1.1(4) | C.6.2(1) | C.6.3(1) | C.7(7) |
| D.3.2(1) | D.3.3(1) | D.3.6(1) | D.4.2(1) |
| D.4.3(1) | E.3.1(3) | E.3.3(1) | E.3.4(1) |
| E.3.5(1) | E.3.5(2) | E.3.5(7) | E.3.6(1) |
| E.3.7(1) | E.4(1) | E.5.1(1) | E.5.1(3) |
| E.5.6(1) | E.7.1(1) | E.8.1(1) | E.8.1(4) |
| E.8.1(5) | E.8.2(1) | E.8.2.2(4) | E.8.2.3(1) |
| E.8.2.4(3) | E.8.2.5(1) | F.1(1) | F.5.3(2) |
| F.9.2(1) | G.1(1) | G.3(2) | H.1(1) |
| H.3(4) | H.5.3.2(1) | H.5.3.4(1) | H.5.4(2) |
| H.5.5.1(1) | H.5.5.2(2) | H.5.5.2(3) | H.5.6.1(1) |
| H.5.6.2(1) | H.5.6.3(1) | H.6.4(2) | I.1(1) |
| J.1(1) | J.4.2.8(4) | J.4.3(1) | J.4.3(2) |
| J.5.3.2.2(2) | J.5.3.2.3(1) | J.5.3.2.8(4) | K.1(1) |
| L.1(1) | M.1(1) |  |  |

National choice is allowed in prEN 1991‑1‑4 on the application of the following informative annexes:

|  |  |  |  |
| --- | --- | --- | --- |
| Annex B | Annex F | Annex G | Annex H |
| Annex I | Annex J | Annex K | Annex L |
| Annex M |  |  |  |

The National Annex can contain, directly or by reference, non-contradictory complementary information for ease of implementation, provided it does not alter any provisions of the Eurocodes.

# Scope

## Scope of prEN 1991‑1‑4

(1) This document gives principles and rules for the determination of natural wind actions for the structural design of building and civil engineering works for each of the loaded areas under consideration. This includes the whole structure or parts of the structure or elements attached to the structure, e.g. components, cladding units and their fixings, safety and noise barriers.

(2) This part is applicable to:

* buildings and civil engineering works with heights up to 300 m;
* bridges having no span greater than 200 m.

(3) This part is intended to predict characteristic wind actions on land-based structures, their components and appendages.

(4) This part is also applicable to structures less than 1 km offshore from the main coastline. For offshore structures more than 1 km from the main coastline, the terrain effects defined in this part do not apply.

(5) This part does not give guidance on non-synoptic winds (e.g. thunderstorms, downbursts, microbursts, tornadoes, etc.), mixed wind climates, nor does it give guidance on how to account for local effects (e.g. thermal effects, funnelling, strong arctic thermal surface inversion, etc.).

(6) This document addresses simplified procedures for dynamic effects, mostly based on the assumption of a dominant single-mode response. General criteria for performing a full dynamic analysis under aerodynamic excitation are not treated in this document.

(7) Wind pressure effects of passing vehicles are outside the scope of this document.

NOTE See EN 1991‑2 for wind effects from passing trains.

## Assumptions

(1) The assumptions given in EN 1990:2023, 1.2 apply.

# Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE See the Bibliography for a list of other documents cited that are not normative references, including those referenced as recommendations (i.e. in ‘should’ clauses), permissions (‘may’ clauses), possibilities ('can' clauses), and in notes.

EN 1990, *Eurocode* — *Basis of structural and geotechnical design*

ISO 2394, *General principles on reliability for structures*

ISO 3898, *Bases for design of structures — Names and symbols of physical quantities and generic quantities*

ISO 8930, *General principles on reliability for structures — Vocabulary*

# Terms, definitions and symbols

## Terms and definitions

For the purposes of this document, the terms and definitions given in EN 1990, ISO 2394, ISO 3898 and ISO 8930 and the following apply.

3.1.1

fundamental basic wind velocity

characteristic 10‑minute mean wind velocity with an annual probability of being exceeded of 0,02, irrespective of wind direction and time of year, at a height of 10 m above ground level in flat open country terrain with large windward fetch of low vegetation such as grass and isolated obstacles with separations of at least 20 obstacle heights, and accounting for altitude effects (if required)

Note 1 to entry: This terrain corresponds to terrain category II in Table 6.1 and is illustrated in B.1.

3.1.2

basic wind velocity

fundamental basic wind velocity modified to account for the annual probability of exceedance, the direction of the wind, the season and the altitude (if required)

3.1.3

mean wind velocity

basic wind velocity modified to account for the effect of terrain roughness, orography and height above ground level

3.1.4

peak factor for turbulence

factor corresponding to a gust duration of approximately 3 seconds, which corresponds to standardized gust durations at meteorological stations

3.1.5

pressure coefficient

coefficient which gives the pressure on the surfaces of buildings or civil engineering works; external pressure coefficients apply to the external surfaces; internal ones to the internal surfaces

3.1.6

net pressure coefficient

coefficient that accounts for the resulting pressure difference across a skin

3.1.7

force coefficient

coefficient that accounts for the overall effect or the effect per unit length of the wind on a structure, structural element or component, including friction, if not specifically excluded

3.1.8

friction coefficient

coefficient that accounts for the effects of wind friction on the external surfaces of buildings and structures

3.1.9

background response factor

factor to allow for the lack of full correlation of the pressure on the structural surfaces

3.1.10

resonance response factor

factor to allow for the amplification of effects of wind turbulence at the natural frequency of the relevant vibration mode

## Symbols

(1) For the purposes of this document, the following symbols apply.

NOTE The notation used is based on ISO 3898. In this part the symbol dot in Formulae indicates the multiplication sign. This notation has been employed to avoid confusion with functional Formulae.

(2) A basic list of notations is provided in EN 1990:2023, 1.6; the additional notations below are specific to prEN 1991‑1‑4.

### Latin upper case letters

|  |  |
| --- | --- |
|  | area |
|  | area swept by the wind |
|  | reference area |
|  | base area |
|  | background response factor |
|  | wind load factor for bridges |
|  | Young’s modulus |
|  | resultant friction force |
|  | vortex exciting force at point j of the structure |
|  | resultant wind force |
|  | height of a topographic feature |
|  | turbulence intensity |
|  | mode shape factor; shape parameter; factor |
|  | aerodynamic damping parameter |
|  | interference factor for vortex shedding |
|  | reduction factor for parapets |
| 𝐾𝑅,L | load distribution factor |
|  | correlation length factor |
|  | non dimensional coefficient |
|  | length of the span of a bridge deck; turbulent length scale; projected length, chord length |
|  | actual length of a leeward slope |
|  | effective length of a windward slope |
|  | correlation length |
|  | actual length of a windward slope |
|  | number of cycles caused by vortex shedding; number |
|  | number of loads for gust response |
|  | member force |
|  | parameter |
|  | wind resistance |
|  | resonant response factor |
|  | Reynolds number |
|  | wind action; load effect |
|  | Scruton number |
|  | non-dimensional power spectral density function for along-wind turbulence |
|  | non-dimensional power spectral density function for lateral wind turbulence |
|  | non-dimensional power spectral density function for vertical wind turbulence |
|  | Strouhal number |
|  | return period |
|  | weight of the structural parts contributing to the stiffness of a chimney |
|  | total weight of a chimney |

### Latin lower case letters

|  |  |
| --- | --- |
|  | factor of galloping instability |
|  | combined stability parameter for interference galloping |
|  | along-wind peak acceleration |
|  | width of the structure (the length of the surface perpendicular to the wind direction if not otherwise specified) |
|  | altitude factor |
|  | dynamic factor |
|  | directional factor |
|  | exposure factor |
|  | force coefficient |
|  | force coefficient of structures or structural elements without free-end flow |
|  | lift force coefficient |
|  | across-wind force coefficient |
|  | friction coefficient |
|  | force coefficient in the across-wind plane |
|  | moment coefficient |
|  | pressure coefficient |
|  | external pressure coefficient |
|  | external local pressure coefficient |
|  | external detailed pressure coefficient |
|  | external global pressure coefficient |
|  | internal pressure coefficient |
|  | net pressure coefficient |
|  | probability factor |
|  | roughness factor |
|  | orography factor |
|  | size factor |
|  | structural factor |
|  | seasonal factor |
|  | depth of the structure (the length of the surface parallel to the wind direction if not otherwise specified) |
|  | eccentricity of a force or edge distance |
|  | non dimensional frequency |
|  | height of the structure |
|  | obstruction height |
|  | displacement height |
|  | equivalent roughness |
|  | peak factor background turbulence |
|  | turbulence factor |
|  | peak factor resonance turbulence |
|  | terrain factor |
|  | peak factor for turbulent wind |
|  | torsional stiffness |
|  | length of a horizontal structure |
|  | mass per unit length |
|  | equivalent mass per unit length |
|  | natural frequency of the structure of the mode |
|  | fundamental frequency of along-wind vibration |
|  | fundamental frequency of across-wind vibration |
|  | fundamental frequency of vertical vibration |
|  | ovalling frequency |
|  | annual probability of exceedance |
|  | reference mean (basic) velocity pressure |
|  | mean velocity pressure |
|  | peak velocity pressure |
|  | radius |
|  | factor; coordinate |
|  | time |
|  | onset wind velocity for galloping |
|  | critical wind velocity for interference galloping |
|  | critical wind velocity of vortex shedding |
|  | divergence wind velocity |
|  | mean wind velocity |
|  | fundamental value of the basic wind velocity |
|  | basic wind velocity |
|  | wind pressure |
|  | horizontal distance in direction of the wind |
| -direction | horizontal direction, perpendicular to the span |
| -direction | horizontal direction along the span |
|  | maximum across-wind amplitude at critical wind speed |
|  | height above ground |
|  | average height |
| -direction | vertical direction |
|  | roughness length |
| , | reference height for external wind action, internal pressure |
|  | distance from the ground to the considered component |
|  | maximum height |
|  | minimum height |
|  | reference height for determining the structural factor |

### Greek upper case letters

|  |  |
| --- | --- |
|  | windward slope |
|  | fundamental along-wind modal shape |
|  | fundamental along-wind modal shape of mode |

### Greek lower case letters

|  |  |
| --- | --- |
|  | galloping instability parameter |
|  | combined stability parameter of interference galloping |
| 𝛽k | critical wind direction |
|  | one-dimensional admittance function |
|  | logarithmic decrement of damping |
|  | logarithmic decrement of aerodynamic damping |
|  | logarithmic decrement of damping due to special devices |
|  | logarithmic decrement of structural damping |
|  | coefficient |
|  | bandwidth factor |
|  | frequency factor |
|  | variable |
|  | solidity ratio, blockage of canopy |
|  | slenderness ratio |
|  | opening ratio, permeability of a skin |
|  | up-crossing frequency; Poisson ratio; kinematic viscosity |
|  | torsional angle; wind direction; angle of wind incidence to the normal in plane; slope |
|  | air density, which depends on the altitude, temperature and barometric pressure to be expected in the region during the relevant wind conditions |
|  | standard deviation of the along-wind turbulence |
|  | standard deviation of the lateral wind turbulence |
|  | standard deviation of the vertical wind turbulence |
|  | angle of wind incidence to the longitudinal axis |
|  | reduction factor for multibay canopies |
|  | reduction factor of force coefficient for square sections with rounded corners |
|  | reduction factor of force coefficient for structural elements with end-effects |
|  | end-effect factor for circular cylinders |
|  | shelter factor for walls and fences |
|  | exponent of mode shape |

### Indices

|  |  |
| --- | --- |
|  | ancillary item |
|  | cable |
|  | circular-section members |
|  | critical |
|  | external; exposure; effective |
|  | face |
|  | flat-sided members |
|  | friction |
|  | guy |
|  | mast height |
|  | internal; mode number |
|  | current number of incremental area or point of a structure |
|  | bare mast or mast only |
|  | mean; mast |
|  | single frame |
|  | peak; parapet; combined effects of patch loads |
|  | patch load |
|  | reference |
|  | structure |
|  | structural scaling factor |
|  | super-critical |
|  | bare tower or only tower |
|  | mean and gust wind |
|  | wind velocity in along-wind direction |
|  | wind velocity in lateral wind direction |
|  | in the direction of the wind |
|  | wind velocity in vertical direction; with wind |
|  | in the across-wind direction |
|  | along-wind direction; in the across-wind direction |
|  | lateral wind direction |
|  | in the vertical direction |
|  | vertical direction; height above ground level |
|  | angle of wind incidence |

# Design situations

(1) The relevant wind actions shall be determined for each design situation identified in accordance with EN 1990.

(2) In accordance with EN 1990, other actions (such as snow, traffic, ice or rain) which can modify the effects of wind actions should be taken into account.

NOTE See also EN 1991‑1‑3 for snow, prEN 1991‑1‑9 for atmospheric icing, and EN 1991‑2 for traffic.

(3) The changes to the structure during construction stages (such as different stages of the form of the structure, dynamic characteristics, etc.), which can modify the effects of wind actions, should be taken into account.

NOTE See also EN 1991‑1‑6 for actions during execution.

(4) Fatigue due to the effects of wind actions should be considered where relevant, see EN 1990.

NOTE Stress ranges and number of load cycles can be obtained from Annex F, G and H.

(5) Structures should be designed to resist wind forces in all directions including torsion.

# Modelling of wind actions

## Representations of wind actions

(1) The wind action shall be represented by a simplified set of pressures or forces whose effects are equivalent to the extreme effects of the turbulent wind.

NOTE 1 Wind actions fluctuate with time and act directly as pressures on the external surfaces of enclosed structures and indirectly on the internal surfaces because of porosity of the external surface. They can also act directly on the internal surface of open structures.

NOTE 2 Pressures acting on a surface results in forces normal to the surface of the structure or of individual cladding components.

NOTE 3 When large areas of structures are swept by the wind, friction forces acting tangentially to the surface can be significant.

NOTE 4 The effect of the wind on the structure (i.e. the response of the structure), depends on the size, shape and dynamic properties of the structure. Wind actions in general include steady and fluctuating components which can be amplified at natural frequencies of the structure. Stiff structures with high natural frequencies respond in a quasi-static way to wind speed fluctuations. Structures with lower frequencies have increasingly important resonant responses, but up to a point they can still be treated as quasi-static.

## Classification of wind actions

(1) Unless otherwise specified, wind actions should be classified as variable free actions.

NOTE See EN 1990 for the classification of actions.

## Characteristic values

(1) The wind actions calculated using prEN 1991‑1‑4 are intended to be characteristic values corresponding to a 2 % probability of being exceeded per year as defined in EN 1990. This is equivalent to a return period of 50 years, see EN 1990.

NOTE 1 EN 1990 provides appropriate partial factors on wind load to reduce the probability of failures to acceptable levels.

NOTE 2 In the case of vortex shedding responses occurring at more frequent wind speeds, rules for calculation of the responses and additional fatigue are provided in Annex H.

NOTE 3 Factored wind speeds are used to ensure that excessive aeroelastic responses due to galloping or flutter will not occur with significant probability within the range of factored wind actions, see Annex H.

NOTE 4 Further guidance concerning the probabilistic description of wind actions is provided in Annex M.

## Loading models

(1) The wind actions on structures should be calculated from:

* the peak velocity pressure according to Clause 6, depending on the wind climate, the terrain roughness and orography, and the reference height,
* and the aerodynamic coefficients:
* the external and internal pressure coefficients given in Annex C for buildings and other structures,
* the net pressure coefficients given in Annex D for walls and roofs, or
* the force coefficients given in Annex E for structures and structural elements.

NOTE 1 Table 5.1 and Table 5.2 describe a design process to assist in the determination of wind velocities, velocity pressures and aerodynamic coefficients, and give reference to relevant clauses and annexes.

NOTE 2 This part covers use of equivalent quasi-static methods where . See 8.2 for guidance on estimating . The clauses below refer to Annexes providing additional guidance for structures which can have significant resonant responses.

Table 5.1 — Guidance for determination of wind velocity and velocity pressure

|  |  |
| --- | --- |
| Determine fundamental value of the basic wind velocity from wind map | 6.2(1) NOTE 1 |
| Determine: |  |
| altitude factor | 6.2(2) NOTE 1 |
| directional factor | 6.2(2) NOTE 2 |
| seasonal factor | 6.2(2) NOTE 3 |
| probability factor | Formula (6.2) |
| Determine: |  |
| basic wind velocity | Formula (6.1) |
| reference height | Annex C, D or E |
| terrain roughness category | 6.3.2 |
| Determine whether orography is significant?  If orography is significant, determine (otherwise ) | 6.3.3  B.3 |
| **If the structure height is < 200 m** | |
| Determine: |  |
| basic velocity pressure | Formula (6.3) |
| If orography is not significant | Figure 6.3 |
| exposure factor | Formula (6.11)  Formula (6.13)  Figure 6.3 |
| peak velocity pressure |  |
| If orography is significant | |
| roughness factor | Formula (6.6) |
| turbulence intensity | Formula (6.10) |
| mean wind velocity | Formula (6.4) |
| peak wind velocity | Formula (6.12) |
| peak velocity pressure | Formula (6.11) |
| **For slender structures up to 300 m height, and can be determined from B.6.** | |

Table 5.2 — Guidance for determination of wind load

|  |  |
| --- | --- |
| **Wind pressures and forces for buildings:** | |
| Obtain: |  |
| external pressure coefficient, | Annex C |
| internal pressure coefficient, | Clause C.5 |
| friction coefficient, | Clause E.7 |
| Determine: |  |
| Wind pressure acting on external surfaces, | Formula (7.2) |
| Wind pressure acting on internal surfaces, | Formula (7.3) |
| Determine: |  |
| Forces from external wind pressure, | Formula (7.6) |
| Forces from internal wind pressure, | Formula (7.7) |
| Forces from friction, | Formula (7.8) |
| Determine wind force as vector sum of , and | Subclause 7.5(4) |
| **Net wind pressures and forces on canopy roofs, porches, balconies, free-standing walls, parapets, fences, and signboards:** | |
| Obtain: |  |
| net pressure coefficient, | Annex D |
| Determine: |  |
| net wind pressure | Subclause 7.3(3) |
| net wind force | Formula (7.5) |
| **Wind forces on elongated structures and structural elements:** | |
| Obtain: |  |
| force coefficient, | Annex E |
| Determine: |  |
| wind force, | Formula (7.4) or Formula (7.5) |
| lattice towers and guyed masts | Annex J |

(3) The following effects of wind-induced vibrations should be estimated when relevant:

* along-wind resonant turbulence giving along-wind buffeting vibrations of flexible structures;
* transverse resonant turbulence giving across-wind buffeting vibrations of flexible structures;
* along-wind resonant turbulence and across-wind resonant turbulence giving torsional buffeting vibrations of flexible structures;
* vortex shedding and other aeroelastic phenomena giving vibrations of flexible structures.

NOTE 1 Procedures for wind-induced vibrations cover structures where only one dominant mode is significant.

NOTE 2 The estimation of peak acceleration considering only the dominant mode is a simplified approach. Estimating local peak acceleration is much more complex.

(4) The along-wind response of flexible structures should be calculated using the structural factor , which is composed of the size factor and the dynamic resonance factor , both contributing to the equivalent static wind action.

NOTE 1 8.2 gives further guidance.

NOTE 2 Table 5.3 describes a design process to assist in the determination of the along-wind buffeting response and gives reference to relevant clauses and annexes.

Table 5.3 — Guidance for determination of structural factor,

|  |  |
| --- | --- |
| Determine:  whether may be used as an appropriate simplifying value | Subclause 8.2 |
| Or:  Evaluate by a more rigorous method | Annex F |

(5) Across-wind response and torsional response should be considered for structures described in Clause 9 and 10.

NOTE Table 5.4 describes a design process to assist in the determination of the across-wind response and gives reference to relevant clauses and annexes.

Table 5.4 — Guidance for determination of across-wind dynamic response

|  |  |
| --- | --- |
| For buildings where , calculation of across-wind dynamic response is not necessary. | – |
| For buildings where , calculate across-wind response. | Clause 9  Annex G |
| For buildings where , calculate across-wind response. | Clause 9  Annex G – Annex H |
| For buildings where , calculate across-wind response. | Clause 9 – Clause 10  Annex H |
| For other flexible, slender structures (e.g. chimneys, bridge decks, etc.), calculate across-wind response. | Clause 10  Annex H |

(6) The aeroelastic response from vortex shedding and other aeroelastic phenomena should be considered for flexible structures and structural members, such as cables and other slender elements, masts, chimneys and bridges.

NOTE Simplified guidance on aeroelastic response is given in Clause 10 and Annex H.

(7) Where the design of the structure is critically dependent on the level of structural damping, for instance for serviceability limit states and across-wind vibrations, the sensitivity to variation in structural damping shall be investigated.

NOTE 1 Values of structural damping given in Annex I are approximate and cannot be lower bound. This can result in the inclusion supplementary damping devices or provision for their retrofit.

NOTE 2 Annexes F, G and H give guidance on the calculations of vibrations.

(8) It should be assessed whether a dynamic response procedure is needed for bridges. If a dynamic response procedure is not needed, may be taken equal to 1,0.

NOTE 1 For normal road and railway bridge decks of less than 40 m span a dynamic response procedure is generally not needed. For the purpose of this categorization, normal bridges are considered to include bridges constructed in steel, concrete, aluminium or timber, including composite construction, and whose shape of cross sections is generally covered by Figure E.1.6.

NOTE 2 The National Annex can give criteria to determine whether a dynamic response procedure is needed for bridges and related procedures.

## Design assisted by testing and measurements

(1) In supplement to calculations, wind tunnel tests and proven and/or properly validated numerical methods may be used to obtain load and response information, using appropriate models of the structure and of the natural wind.

NOTE 1 See EN 1990:2023, 7.3(3) for achievement of the level of reliability required.

NOTE 2 Annex K gives further guidance on wind tunnel tests and numerical simulations.

(2) Load and response information and terrain parameters may be obtained from appropriate full scale data.

# Wind velocity and velocity pressure

## Basis for calculation

(1) The wind velocity and the velocity pressure should be considered to be composed of a mean and a fluctuating component.

(2) The mean wind velocity should be determined from the basic wind velocity which depends on the wind climate as described in 6.2, and on height above ground level, as described in 6.3.

NOTE 1 Procedures for terrain roughness are set out in 6.3.2 for structures not exceeding 200 m.

NOTE 2 Orography is explained in 6.3.3 and procedures calculating orography are set out in B.3.

NOTE 3 The peak velocity pressure is determined from 6.5.

(3) The fluctuating component of the wind should be represented by the turbulence intensity defined in 6.4.

NOTE 1 Annex B provides guidance for slender structures taller than 200 m and up to 300 m.

NOTE 2 The National Annex can give guidance on the application of Annex B for structures lower than 200 m.

NOTE 3 The National Annex can provide National climatic information from which the mean wind velocity and the peak velocity pressure can be directly obtained for the terrain categories considered.

NOTE 4 Table 5.1 contains a design process to assist in the determination of the peak velocity pressure.

NOTE 5 The basis for calculation covers structures less than 1 km offshore from the main coastline.

NOTE 6 The National Annex can provide additional guidance for structures with a distance from the main coastline exceeding 1 km, see 1.1(4).

## Basic values

(1) The basic wind velocity should be calculated from the fundamental value of the basic wind velocity , defined as the characteristic 10-minute mean wind velocity with an annual probability of being exceeded of 0,02, irrespective of wind direction and time of year, at a height of 10 m above ground level in flat open country terrain with large windward fetch of low vegetation such as grass and isolated obstacles with separations of at least 20 obstacle heights.

NOTE  The fundamental value of the basic wind velocity can be set in the National Annex.

(2)P The basic wind velocity, should be calculated from Formula (6.1).

|  |  |
| --- | --- |
|  | (6.1) |

where

|  |  |
| --- | --- |
|  | is the fundamental value of the basic wind velocity; |
|  | is the altitude factor; |
|  | is the directional factor; |
|  | is the seasonal factor; |
|  | is the probability factor |

NOTE 1 The value of is 1,0 unless the National Annex gives a different value.

NOTE 2 The value of the directional factor, , for various wind directions is 1,0 unless the National Annex gives a different value.

NOTE 3 The value of the seasonal factor, , is 1,0 unless the National Annex gives a different value.

(3) For temporary structures and for all structures in the execution phase, the seasonal factor may be used. For transportable structures, which can be used at any time in the year, should be taken equal to 1,0.

NOTE See also EN 1991‑1‑6.

(4) The probability factor, should be calculated from Formula (6.2):

|  |  |
| --- | --- |
|  | (6.2) |

where

|  |  |
| --- | --- |
|  | is the shape parameter depending on the coefficient of variation of the extreme-value distribution; |
|  | is the exponent; |
|  | is the annual probability of exceedance; |
|  | is the return period in years where . |

NOTE 1 The probability factor, is multiplied with the basic wind velocity to calculate the 10 minutes mean wind velocity having the probability for an annual exceedance.

NOTE 2 The shape parameter is equal to defined in Annex M.

NOTE 3 The values for and are 0,2 and 0,5, respectively, unless the National Annex gives a different value. These values correspond to a coefficient of variation of 0,23 for the annual maximum velocity pressure.

NOTE 4 See also EN 1991‑1‑6 for actions during execution.

(5) The basic velocity pressure shall be calculated from Formula (6.3):

|  |  |
| --- | --- |
|  | (6.3) |

where

|  |  |
| --- | --- |
|  | is the air density. |

NOTE The value for is 1,25 kg/m3 unless the National Annex gives different values.

## Mean wind velocity and pressure

### Variation with height

(1) The mean wind velocity at a height above the terrain depends on the terrain roughness and orography and on the basic wind velocity, , and should be determined using Formula (6.4):

|  |  |
| --- | --- |
|  | (6.4) |

where

|  |  |
| --- | --- |
|  | is the roughness factor, given in 6.3.2; |
|  | is the orography factor, taken as 1,0 unless otherwise specified in 6.3.3. |

NOTE 1 If the orography is accounted for in the basic wind velocity, the value of is 1,0, unless a different value is given in the National Annex.

NOTE 2 Design charts or tables for can be given in the National Annex.

(2) The influence of neighbouring structures on the wind velocity should be considered (see 6.3.4).

(3) The mean velocity pressure at height , should be determined using Formula (6.5):

|  |  |
| --- | --- |
| = | (6.5) |

where

|  |  |
| --- | --- |
|  | is the air density. |

NOTE The mean of the fluctuating component squared has been disregarded in the determination of the mean velocity pressure. See also F.5.3(1) Note 2.

### Terrain roughness

(1) The roughness factor, , should account for the variability of the mean wind velocity at the site of the structure due to:

* the height above ground level
* the terrain roughness windward of the structure in the wind direction considered

NOTE Unless the National Annex gives a different procedure, the procedure for the determination of the roughness factor at height , is given in (2) when the windward distance with uniform terrain roughness is long enough to stabilise the profile sufficiently, see (3).

(2) The procedure for the determination of the roughness factor at height , should be taken as defined in Formula (6.6) and is based on a logarithmic velocity profile.

|  |  |  |  |
| --- | --- | --- | --- |
|  | for |  | (6.6) |
|  | for |  |  |

where

|  |  |
| --- | --- |
|  | is the roughness length; |
|  | terrain factor depending on the roughness length calculated using Formula (6.7) |

|  |  |
| --- | --- |
|  | (6.7) |

where

|  |  |
| --- | --- |
|  | = 0,05 m (terrain category II, Table 6.1); |
|  | is the minimum height defined in Table 6.1; |
|  | is to be taken as 200 m. |

, depend on the terrain category. Values are given in Table 6.1 depending on five representative terrain categories.

Table 6.1 — Terrain categories and terrain parameters

| Terrain category | |  |  |
| --- | --- | --- | --- |
| [m] | [m] |
| 0 | Sea or coastal area exposed to the open sea | 0,003 | 1 |
| I | Lakes or flat and horizontal area with negligible vegetation and without obstacles | 0,01 | 1 |
| II | Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights | 0,05 | 2 |
| III | Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest) | 0,3 | 5 |
| IV | Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m | 1,0 | 10 |
| NOTE The terrain categories are illustrated in Figure B.1. | | | |

(3) The lowest terrain roughness category in an angular sector around the wind direction, as defined in Figure 6.1, should be used for a given wind direction. Small areas (less than 10 % of the area under consideration) with deviating roughness may be ignored, see Figure 6.1. The minimum windward distance that should be considered is shown in Figure 6.2, as a function of the height of the structure above terrain.

|  |  |
| --- | --- |
|  | (6.8) |

where

|  |  |
| --- | --- |
|  | is the reference windward distance of 1 km; |
|  | is the reference height of 23,2 m. |

Ein Bild, das Diagramm, Reihe, Entwurf, Zeichnung enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | nominal angular sector |
| 2 | windward distance is calculated using Formula (6.8) |
| 3 | consideration area |
| 4 | area with deviating roughness |

Figure 6.1 — Assessment of terrain roughness

Ein Bild, das Diagramm, Reihe, Text, parallel enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| *h* | building height, in metres |
| *X* | minimum windward distance, in kilometres |

Figure 6.2 — Minimum windward distance for obtaining uniform terrain roughness for a building height

NOTE 1 The value of the angular sector can be taken as the 30° angular sector within ±15° from the wind direction unless the National Annex gives a different value.

NOTE 2 The value for the windward distance can be set in the National Annex.

(4) When a pressure or force coefficient is defined for a nominal angular sector, the lowest roughness length within any 30° angular wind sector should be used.

(5) When there is choice between two or more terrain categories in the definition of a given area, then the area with the lowest roughness length should be used.

(6) The windward distance in Figure 6.2 is calculated using Formula (6.8).

### Terrain orography

(1) Orography affects the wind flow and may increase the wind velocity. The effects of orography may be neglected when the average slope of the windward terrain is less than 5%. The windward terrain may be considered up to a distance of 10 times the height of the isolated orographic feature.

(2) Where orography (e.g. hills, cliffs etc.) has an average slope of more than 5 %, the effects should be taken into account using the orography factor .

NOTE 1 B.3 gives guidance for determining unless the National Annex gives a different procedure.

NOTE 2 The procedure given in B.3 applies to well defined hills and escarpments, surrounded by relatively flat terrain. In more complex terrain, or where the design is critically dependent on the assessment of orography, more detailed investigation is described in Annex K.

NOTE 3 In complex terrain, where the windward slope cannot be defined clearly, additional guidance can be given in the National Annex.

### Large and considerably higher neighbouring structures

(1) If the structure is to be located close to another structure, which is at least twice as high as the height of the structure considered, then increased wind velocities for certain wind directions should be considered, depending on the properties of the higher structure

NOTE B.4 gives guidance on determining the influence of higher neighbouring structures.

### Closely spaced buildings and obstacles

(1) The effect of closely spaced buildings and other obstacles may be taken into account.

NOTE In rough terrain, closely spaced buildings modify the mean wind flow near the ground, as if the ground level was raised to a height called the displacement height . B.5 gives guidance on effect of closely spaced buildings.

## Wind turbulence

(1) The turbulence intensity at height should be taken equal to the standard deviation of the turbulence divided by the mean wind velocity.

(2) The turbulent component of wind velocity has a mean value of 0 and a standard deviation . The standard deviation of the turbulence may be determined using Formula (6.9).

|  |  |
| --- | --- |
|  | (6.9) |

NOTE 1 For the terrain factor see Formula (6.7), for the basic wind velocity see Formula (6.1), k1 is the turbulence factor.

NOTE 2 The value for turbulence factor is 1.0 unless the National Annex gives a different value.

(3) may be calculated from Formula (6.10).

|  |  |  |  |
| --- | --- | --- | --- |
|  | for |  | (6.10) |
|  | for |  |  |

where

|  |  |
| --- | --- |
|  | is the turbulence factor. |

NOTE The value of is 1.0 unless the National Annex gives a different value.

(4) For mean wind velocities lower than , stratified flow with zero turbulence should be considered for vortex-induced vibrations, see Annex H for further guidance.

NOTE Unless otherwise specified in the National Annex, is equal to 15 m/s.

## Peak wind velocity and velocity pressure

(1) The peak velocity pressure at height , which includes mean and short-term velocity fluctuations, should be determined by using the Formula (6.11).

|  |  |
| --- | --- |
|  | (6.11) |

where

|  |  |
| --- | --- |
|  | is the air density; |
|  | is the peak wind velocity given in Formula (6.12); |

NOTE 1 A different rule can be given in the National Annex.

|  |  |
| --- | --- |
|  | (6.12) |

NOTE 2 The value of the peak factor for turbulence is unless the National Annex gives a different value. The peak factor for turbulence is consistent with the values of the aerodynamic coefficients specified in Annexes C to E.

(2) The exposure factor at height should be calculated from Formula (6.13).

|  |  |
| --- | --- |
|  | (6.13) |

where is given in (1) and is given in Formula (6.3).

(3) For flat terrain where (see 6.3.3), the exposure factor is illustrated in Figure 6.3 as a function of height above terrain and a function of terrain category as defined in Table 6.1.

Ein Bild, das Text, Diagramm, Reihe, parallel enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| *c*e | exposure factor |
| *z* | height above ground, in metres |

Figure 6.3 — Exposure factor for ,

# Wind actions

## General

(1) Wind actions on structures and structural elements shall be determined taking account of both external and internal wind pressures.

NOTE A summary of calculation procedures with reference to relevant clauses and annexes is given:

* in Table 5.1 for the determination of wind velocity and velocity pressure;
* in Table 5.2 for the determination of wind load.

(2) For structures with a circular cross-section, the wind action depends on the Reynolds number, , defined by Formula (7.1):

|  |  |
| --- | --- |
|  | (7.1) |

where

|  |  |
| --- | --- |
|  | is the wind velocity, see Formula (6.12); |
|  | is the diameter; |
|  | is the kinematic viscosity of the air |

NOTE 1 The value of is unless the National Annex gives a different value.

NOTE 2 The flow around circular cross-sections and thereby the wind action depends on the particular Reynolds number regime being either sub-, super- or transcritical.

(3) The wind velocity used to calculate the Reynolds number may be the mean wind velocity or the peak wind velocity,

NOTE See Annexes C and E for further clarification for a particular structure.

## Choice of aerodynamic coefficient

(1) Pressure coefficients defined in 7.3 should be determined for buildings using:

* C.2, C.3 and C.4 for external pressures,
* C.5 for internal pressures.

(2) Net pressure coefficients defined in 7.4 should be determined for:

* canopy roofs, porches and balconies using D.1,
* free-standing walls, parapets, fences and signboards using D.2.

(3) Force coefficients defined in 7.5 should be determined for:

* elongated structures and structural elements, using E.1,
* spheres, using E.2,
* lattice structures, using E.3,
* flags, using E.4,
* bridges, using E.6.

(4) Friction coefficients defined in 7.5 should be determined for walls and surfaces as specified in E.6.

(5) A reduction factor depending on the effective slenderness of the structure may be applied, using E.1.7.

NOTE Force coefficients give the overall effect or effect per unit length of the wind on a structure, structural element or component, including friction, if not specifically excluded.

## Wind pressure on surfaces

(1) The wind pressure acting on the external surfaces, , should be obtained from Formula (7.2).

|  |  |
| --- | --- |
|  | (7.2) |

where

|  |  |
| --- | --- |
|  | is the peak velocity pressure defined in 6.5; |
|  | is the reference height for the external pressure given in Annex C; |
|  | is the pressure coefficient for the external pressure, given in Annex C. |

(2) The wind pressure acting on the internal surfaces of a structure, , should be obtained from Formula (7.3)

|  |  |
| --- | --- |
|  | (7.3) |

where

|  |  |
| --- | --- |
|  | is the peak velocity pressure defined in 6.5; |
|  | is the reference height for the internal pressure given in Annex C; |
|  | is the pressure coefficient for the internal pressure given in Annex C. |

(3) Pressure, directed towards the surface should be taken as positive, and suction, directed away from the surface as negative (Figure 7.1).

Ein Bild, das Diagramm, technische Zeichnung, Plan enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | positive internal pressure |
| 2 | negative internal pressure |

Figure 7.1 — Pressure on surfaces

## Net pressure on surfaces

(1) The net pressure, , is the difference between the pressures on opposite surfaces of an object taking due account of their signs.

(2) Net pressure coefficients should be taken from Annex D.

## Wind forces

(1) The wind forces for the whole structure or a structural member should be determined:

* by calculating forces using force coefficients, see (2) or
* by calculating forces from surface pressures, see (3)

(2) The wind force acting on a structure or a structural member as a whole or per unit length may be determined directly by using Formula (7.4)

|  |  |
| --- | --- |
|  | (7.4) |

or by vector summation over the individual structural member by using Formula (7.5)

|  |  |
| --- | --- |
|  | (7.5) |

where

|  |  |
| --- | --- |
|  | is the structural factor as defined in Clause 8; |
|  | is the force coefficient for the structure or structural member, given in Annex E; |
|  | is the peak velocity pressure defined in 6.5 at reference height of the structure or the member defined in Annex E; |
|  | is the reference area of the structure or structural member as a whole or per unit length, given in Annex E. |

NOTE Annex E gives values for structures or structural members such as prisms, cylinders, roofs, signboards, plates and lattice structures etc.

(3) The wind force, acting on a structure or a structural member may be determined by vector summation of the forces , and calculated from the external and internal pressures using Formulae (7.6) and (7.7) and the frictional forces resulting from the friction of the wind parallel to the external surfaces, calculated using Formula (7.8).

external forces:

|  |  |
| --- | --- |
|  | (7.6) |

internal forces:

|  |  |
| --- | --- |
|  | (7.7) |

friction forces:

|  |  |
| --- | --- |
|  | (7.8) |

where

|  |  |
| --- | --- |
|  | is the structural factor as defined in Clause 8; |
|  | is the external pressure on the individual surface at height , given in Formula (7.2); |
|  | is the internal pressure on the individual surface at height , given in Formula (7.3); |
|  | is the reference area of the individual surface; |
|  | is the friction coefficient derived from Annex E; |
|  | is the area of external surface parallel to the wind, given in Annex E. |

NOTE 1 For elements (e.g. walls, roofs), the wind force becomes equal to the difference between the external and internal resulting forces.

NOTE 2 Friction forces act in the direction of the wind components parallel to external surfaces.

NOTE 3 The resulting force from this summation is not necessarily in the direction of the wind, especially if the structure is not symmetrical.

NOTE 4 This summation can be ignored for calculation of overall building forces unless the ground is sloping, or the calculation refers to part of a building.

(4) The effects of wind friction on the surface may be disregarded when the total area of all surfaces parallel with (or at a small angle to) the wind is equal to or less than 4 times the total area of all external surfaces perpendicular to the wind (windward and leeward).

(5) The mean wind force acting on a structure may be determined directly by using Formula (7.9)

|  |  |
| --- | --- |
|  | (7.9) |

or by vector summation over the individual structural members by using Formula (7.10)

|  |  |
| --- | --- |
|  | (7.10) |

where

|  |  |
| --- | --- |
|  | is the force coefficient for the structure or structural member, given in Annex E; |
|  | is the mean velocity pressure defined in 6.3 at reference height of the structure or the member defined in Annex E; |
|  | is the reference area of the structure or structural member as a whole or per unit length, given in Annex E. |

NOTE Mean wind forces are applied in Annex E, F and J.

(6) The mean wind force, acting on a structure or a structural member may be determined by vector summation of the forces and calculated from the external and internal pressures using Formulae (7.11) and (7.12).

external forces:

|  |  |
| --- | --- |
|  | (7.11) |

internal forces:

|  |  |
| --- | --- |
|  | (7.12) |

(7) In the summation of the wind forces acting on building structures, the lack of correlation of wind pressures between the windward and leeward sides may be taken into account.

# Structural factor

## General

(1) The structural factor takes into account the effect on wind actions from the non-simultaneous occurrence of peak wind pressures on the surface together with the effect of the along-wind vibrations of the structure due to along-wind turbulence.

NOTE 1 Table 5.3 givesguidance for the determination of structural factor .

NOTE 2 can be derived using the detailed procedures in Annex F.

## Approximate determination of

(1) may be taken as unity if any of the following criteria are satisfied:

1. For buildings with a height less than 15 m.
2. For structures having a first natural frequency greater than 5 Hz.
3. For buildings up to 100 m high with a height less than 4 times the in-wind depth, and that have full height regular shear or cross-braced walls.
4. Bridge decks within the scope of E.6.1 and where a dynamic response procedure is not necessary, see 5.5 (8).

NOTE 1 Figure 8.1 for multi-storey buildings and Figure 8.2 for chimneys show geometrical conditions for conservative structural factors being less than or equal to 1, when the basic wind velocity is less than 28 m/s.

NOTE 2 The dynamic response of flexible façade and roof elements is covered by CEN/TS 19100-2.

NOTE 3 The procedure for calculating 𝑐sd covers flexible façade and roof elements with a natural frequency in the range of 3 Hz to 5 Hz. For natural frequencies above 5 Hz no dynamic effects are expected to occur and 𝑐sd can be taken as 1,0.

Ein Bild, das Reihe, Diagramm, Text enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
|  | multi-storey steel buildings |
|  | multi-storey concrete buildings  dimensions of *h* and *d* are given in m |

NOTE 4 Figure 8.1 based on:

Building with rectangular ground plan and vertical external walls, with regular, distribution of stiffness and mass

|  |  |
| --- | --- |
| Roughness length |  |
| Basic wind velocity |  |
| Logarithmic decrement of aerodynamic damping |  |
| Logarithmic decrement of structural damping for steel |  |
| Logarithmic decrement of structural damping for concrete |  |

The natural frequencies are estimated using the Formulae given in Annex I.

Figure 8.1 — = 1,0 for multi-storey steel and concrete buildings as function of across-wind width

Ein Bild, das Reihe, Diagramm, Text, parallel enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
|  | steel chimneys without liners |
|  | concrete chimneys without liners |
|  | steel chimneys with liners  dimensions of *h* and *d* are given in m |

NOTE 5 Figure 8.2 based on:

|  |  |
| --- | --- |
| Roughness length |  |
| Basic wind velocity |  |
| Logarithmic decrement of aerodynamic damping |  |

NOTE 6 Specific based on Annex I:

Concrete chimneys without liners:

, and

Steel chimneys without liners:

, and

Steel chimneys with liners:

and

|  |  |
| --- | --- |
|  |  |
|  |  |
|  |  |

The natural frequencies are estimated using the Formulae given in Annex I.

Figure 8.2 — = 1,0 for chimneys

## Serviceability assessments

(1) For serviceability assessments, displacements and accelerations of the structure at height *z* should be used.

(2) For the along-wind displacement, the equivalent static wind force defined in 7.5 should be used.

NOTE Methods for determining displacements and accelerations are given in Annexes F, G and H.

# Across-wind and torsional actions on buildings

(1) The effects of across-wind and torsional-wind actions should be assessed for buildings.

NOTE 1 For these effects are taken into account by the loading models in 5.4 see also 7.5(3).

NOTE 2 Annex G contains procedures applicable to rectangular plan buildings when where , and are the width, depth and height of the building.

NOTE 3 For buildings with in the range of 6 to 8, Annex G can still be used, but the results it provides are not necessarily conservative. For buildings with in this range, the approach presented in H.4 and H.5 for slender structures can also be used, provided the building has a low value of the generalized Scruton Number.

NOTE 4 An approach for buildings with greater than 8 is given in H.4 and H.5.

NOTE 5 Limiting values of the generalized Scruton Number for the use of H.4 and H.5 can be provided by the National Annexes.

# Aeroelastic phenomena

## General

(1) The effects of aeroelastic phenomena should be assessed.

NOTE  Annex H contains guidance for flexible, slender structures (e.g. chimneys, bridge decks, etc.). Annex H contains procedures applicable also to buildings when , see 9.

## Basis for calculation

(1) The procedures given in this Clause should be used for single, slender structures with uniform sharp edged or circular cross-sections and an approximately uniform distribution of mass along their length.

NOTE Annex H provides guidance for calculation methods applicable to other types of structures.

(2) The dynamic properties of the structure, including natural frequencies and equivalent mass per unit length, should be determined.

NOTE 1 Annex I provides guidance for determination of dynamic properties of the structure.

NOTE 2 Figure 10.1 and 10.2 illustrate when the vortex-induced wind action are based on H.3, i.e. when the peak base moment from vortex-induced vibrations is larger than the peak base moment from along-wind dynamic response . The figures cover square buildings and chimneys. For selected ratios of the equivalent mass defined in Annex I and the air mass the limit is shown as a function of the ratio between the critical wind velocity for vortex-induced vibrations and the mean wind velocity, , and the logarithmic decrement of structural damping, .

Ein Bild, das Text, Reihe, Diagramm, parallel enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
|  | *m*e/(*ρ⋅b⋅d*) = 250 |
|  | *m*e/(*ρ⋅b⋅d*) = 500 |
|  | *m*e/(*ρ⋅b⋅d*) = 750 |
| Ein Bild, das Screenshot, Rechteck, Schwarz, Rahmen enthält.  Automatisch generierte Beschreibung | steel |
| Ein Bild, das Rechteck, Screenshot, weiß, Bilderrahmen enthält.  Automatisch generierte Beschreibung | reinforced concrete |

NOTE 1 Figure 10.1 is based on:

|  |  |
| --- | --- |
| Geometry and mode shape: |  |
| Height |  |
| Height-to-width ratio |  |
| Width-to-depth ratio |  |
| Mode shape | Linear |
| Along wind response: |  |
| Roughness length |  |
| Force coefficient |  |
| Structural factor |  |
| Vortex induced vibrations: |  |
| Peak factor |  |
| Aerodynamic constant |  |
| Aerodynamic damping parameter |  |
| Aerodynamic damping deflection term |  |

The range of typical damping values for steel and reinforced concrete buildings are shown shaded grey.

Figure 10.1 — Base moment for square buildings — No vortex-induced vibrations when

Ein Bild, das Text, Reihe, Diagramm, parallel enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
|  | *m*e/(*ρ⋅b⋅d*) = 50 |
|  | *m*e/(*ρ⋅b⋅d*) = 100 |
|  | *m*e/(*ρ⋅b⋅d*) = 200 |
| Ein Bild, das Screenshot, Rechteck, Schwarz, Rahmen enthält.  Automatisch generierte Beschreibung | Steel |
| Ein Bild, das Rechteck, Screenshot, weiß, Bilderrahmen enthält.  Automatisch generierte Beschreibung | Reinforced concrete |

NOTE 2 Figure 10.2 is based on:

|  |  |
| --- | --- |
| Geometry and mode shape: |  |
| Height |  |
| Height-to-width ratio |  |
| Width-to-depth ratio |  |
| Mode shape | Parabolic |
| Along wind response: |  |
| Roughness length |  |
| Force coefficient |  |
| Structural factor |  |
| Vortex induced vibrations: |  |
| Peak factor |  |
| Aerodynamic constant |  |
| Aerodynamic damping parameter |  |
| Aerodynamic damping deflection term |  |

The range of typical damping values for steel and reinforced concrete chimneys are shown shaded grey.

Figure 10.2 — Base moment for chimneys — No vortex-induced vibrations when

## Galloping

(1) Galloping may be neglected in single, free-standing circular cylinders with constant cross-section, unless subject to accretion of asymmetric ice or at critical Reynolds numbers where flow transitions from sub- to super-critical regime can lead to the so-called dry galloping.

NOTE 1 Galloping is a self-induced vibration of a flexible structure in across-wind bending mode. Non-circular cross-sections including L‑, I‑, U‑ and T‑sections are prone to galloping.

NOTE 2 Ice can cause a stable cross-section to become unstable.

NOTE 3 For circular structures with variable surface roughness and asymmetry, inclined flow, and presence of water rivulets or other features can promote the risk of galloping, especially in the range of the critical Reynolds number transition, noting that this varies with surface roughness and other factors including incident small-scale turbulence.

NOTE 4 Galloping oscillation starts at a special onset wind velocity and normally the amplitudes increase rapidly with increasing wind velocity.

NOTE 5 Annex H provides criteria and procedures to estimate the critical divergence velocity, and methods pertaining to galloping of coupled cylinders and interference galloping.

## Divergence and flutter

(1) Divergence and flutter shall be avoided, as they are likely to lead to structural collapse.

NOTE 1 Static torsional divergence and flutter vibrations are instabilities that occur for flexible plate-like structures, such as signboards, cantilever roofs or suspension-bridge decks, above a certain threshold or critical wind velocity. The instability is caused by the deflection of the structure modifying the aerodynamics to alter the loading.

NOTE 2 Annex H provides criteria and procedures to estimate the critical divergence velocity.

## Wake buffeting

(1) For slender buildings (), chimneys () and cooling towers in tandem or grouped arrangement, the effect of increased turbulence in the wake of nearby structures (wake buffeting) should be taken into account.

(2) Wake buffeting effects may be neglected if at least one of the following conditions applies:

* The distance between two structures referred in (1) is larger than 25 times the across-wind dimension of the upstream building or chimney.
* The natural frequency of the downstream building or chimney is higher than 1 Hz.

(3) If none of the conditions in (1) or (2) are fulfilled, wind tunnel tests should be performed, or specialist advice should be sought.

1. (informative)  
     
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   1. Editorial Note

Annex A has been removed. Due to the time constraints, the size of the document and the numerous elements (formulae, figures, tables, cross references) in the annexes that will require manual renumbering, the relevant editing will take place as appropriate after CEN Enquiry.

1. (informative)  
     
   Terrain effects
   1. Use of this annex

(1) This Informative Annex provides complementary/supplementary guidance to 6 for the treatment of terrain effects.

NOTE National choice on the application of this Informative Annex is given in the National Annex. If the National Annex contains no information on the application of this Informative Annex, it can be used.

* 1. Scope and field of application

(1) This Informative Annex gives illustrations of the terrain categories.

(2) It gives an alternative equilibrium wind model applicable for slender structures with heights up to 300 m above terrain.

(3) It provides rules to calculate the effects of orography and roughness changes, and the influence of neighbouring structures.

(4) It provides a method for calculation of the displacement height, .

* 1. Illustrations of the upper roughness of each terrain category

(1) Terrain should be categorised to derive wind actions on a structure.

NOTE Terrain categories are illustrated in Figure B.1, to complement the descriptions given in Table 6.1. The National Annex can provide alternative images or sketches to illustrate regional differences.

|  |  |
| --- | --- |
| **Terrain category 0**  Sea, coastal area exposed to the open sea | Ein Bild, das Zeichnung, Entwurf, Schwarzweiß, Darstellung enthält.  Automatisch generierte Beschreibung |
| **Terrain category I**  Lakes or area with negligible vegetation and without obstacles | Ein Bild, das Reihe, Zeichnung, Entwurf, parallel enthält.  Automatisch generierte Beschreibung |
| **Terrain category II**  Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights | Ein Bild, das Zeichnung, Entwurf, Schwarzweiß enthält.  Automatisch generierte Beschreibung |
| **Terrain category III**  Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest) | Ein Bild, das Entwurf, Zeichnung, Schwarzweiß enthält.  Automatisch generierte Beschreibung |
| **Terrain category IV**  Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m | Ein Bild, das Zeichnung, Entwurf, Schwarzweiß, Kunst enthält.  Automatisch generierte Beschreibung |

Figure B.1 — Terrain categories

* 1. Transition between terrain categories 0, I, II, III and IV
     1. General

(1) The transition between terrain categories of different roughness lengths shall be considered when calculating the peak velocity pressure, and the structural factor, .

(2) The procedure to account for the transition between terrain categories of increasing roughness length in the wind direction shall be either Procedure 1 or Procedure 2.

NOTE The choice between Procedure 1 and Procedure 2 can be given in the National Annex.

* + 1. Procedure 1

(1) When using Procedure 1, the terrain category with the lower roughness length in the windward direction should be used, provided that the structure is situated near a change of terrain category at a distance:

* less than 2 km from the smoother terrain category 0;
* less than 1 km from the smoother terrain categories I to III.

(2) Small areas (less than 10 % of the area under consideration) with deviating roughness may be ignored.

* + 1. Procedure 2

(1) When using Procedure 2, the following steps should be followed:

1. Determine the terrain categories for the upstream terrain in the angular sectors to be considered.
2. For every angular sector, determine the distance from the building to the upstream boundary between terrain categories.
3. If the distance from the building to a boundary with a terrain category with lower roughness length is smaller than the values given in Table B.1, then the smoother terrain category is used for the angular sector considered. If this distance *x* is larger than the value in Table B.1, the rougher terrain category is used.

(2) Small areas (less than 10 % of the area under consideration) with deviating roughness length may be ignored.

(3) Where no distance is given in Table B.1 or for heights exceeding 50 m, the smoother terrain category should be used.

(4) For intermediate values of height , linear interpolation may be used.

(5) A building in a certain terrain category may be calculated in a smoother terrain category if it is situated within the distance limits defined in Table B.1.

NOTE 1 Procedures 1 and 2 only deal with transitions between terrain categories of increasing roughness length in the wind direction and they result in the selection of conservative equilibrium wind and turbulence profiles. The National Annex can give alternative procedures to address other sequences of transition in terrain category and give non-equilibrium profiles.

NOTE 2 The method given in the ESDU Wind Engineering Data Item 84011 is general and can be used to account for any sequence of change in upstream roughness length and give the corresponding non-equilibrium wind and turbulence profiles.

Table B.1 — Distance

|  |  |  |
| --- | --- | --- |
| Height above ground | I to II | I to III |
| 5 m | 0,50 km | 5,00 km |
| 7 m | 1,00 km | 10,00 km |
| 10 m | 2,00 km | 20,00 km |
| 15 m | 5,00 km |  |
| 20 m | 12,00 km |  |
| 30 m | 20,00 km |  |
| 50 m | 50,00 km |  |
| **Height above ground,** | **II to III** | **II to IV** |
| 5 m | 0,30 km | 2,00 km |
| 7 m | 0,50 km | 3,50 km |
| 10 m | 1,00 km | 7,00 km |
| 15 m | 3,00 km | 20,00 km |
| 20 m | 7,00 km |  |
| 30 m | 10,00 km |  |
| 50 m | 30,00 km |  |
| **Height above ground,** | **III to IV** |
| 5 m | 0,20 km |
| 7 m | 0,35 km |
| 10 m | 0,70 km |
| 15 m | 2,00 km |
| 20 m | 4,50 km |
| 30 m | 7,00 km |
| 50 m | 20,00 km |

* 1. Orography coefficients

(1) In the vicinity of isolated hills and ridges or cliffs and escarpments, mean wind velocities will increase, dependent on the upstream slope in the wind direction, where the height and the length should be taken as defined in Figure B.2.

Ein Bild, das Diagramm, Reihe, technische Zeichnung, Plan enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| *v*m | mean wind velocity at height z above terrain |
| *v*mf | mean wind velocity above flat terrain |
| *c*o | = *v*m/*v*mf |

Figure B.2 — Illustration of increase of wind velocities over orography

(2) The effect of orography on the standard deviation of the turbulence (should be taken as defined in 6.4(1)) may be neglected, it only affects the mean wind velocity, .

NOTE 1 The turbulence intensity will decrease with increasing mean wind velocity and unchanged standard deviation of turbulence.

NOTE 2 The largest increase of wind velocities occurs near the crest of the topographic feature (i.e. .

(3) The effects of orography should be taken into account in the following situations:

For sites on windward slopes of hills and ridges:

* where and

1. For sites on leeward slopes of hills and ridges:

* where and
* where and

1. For sites on windward slopes of cliffs and escarpments:

* where and

1. For sites on leeward slopes of cliffs and escarpments:

* where and
* where and

(4) The orography factor, and should be defined by:

|  |  |  |  |
| --- | --- | --- | --- |
|  | for |  | (B.1) |
|  | for |  | (B.2) |
|  | for |  | (B.3) |

where

|  |  |
| --- | --- |
|  | is the orographic location factor, to be obtained from Figure B.3 or Figure B.4 scaled to the length of the effective windward slope length, ; |
|  | is the windward slope in the wind direction (see Figure B.4); |
|  | is the effective length of the windward slope, should be taken as defined in Table B.2; |
|  | is the actual length of the windward slope in the wind direction; |
|  | is the actual length of the leeward slope in the wind direction; |
|  | is the effective height of the feature; |
|  | is the horizontal distance of the site from the top of the crest (positive leeward); |
|  | is the vertical distance from the ground level of the site. |

NOTE The orography factor, accounts for the increase of mean wind speed over isolated hills, ridges, cliffs and escarpments (not undulating and mountainous regions). It is related to the wind velocity at the base of the hill, ridge, cliff or escarpment.

Table B.2 — Values of the effective length

| Type of slope () | |
| --- | --- |
| **Shallow** () | **Steep** () |
|  |  |

(5) In valleys, may be set to 1,0 if no speed up due to funnelling effects is to be expected. For structures situated within, or for bridges spanning steep-sided valleys, care should be taken to account for any increase of wind speed caused by funnelling.

NOTE  The National Annex can provide additional guidance to determine whether orography is significant.



Key

|  |  |
| --- | --- |
| 2 | site |
| 3 | crest |
| a | downwind slope |

Figure B.3 — Factor *s* for cliffs and escarpments

Ein Bild, das Diagramm, Entwurf, Reihe, Zeichnung enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 2 | site |
| 3 | crest |
| a | downwind slope |

Figure B.4 — Factor *s* for hills and ridges

(6) Formulae (B.4), (B.7) and (B.11) should be used to compute the value of orographic location factor, . As those Formulae are empirical, values of the parameters used should be restricted to the stated ranges, otherwise invalid values can be generated.

1. windward section for all orography Figure B.3:

For the ranges

the orographic location factor, should be calculated from Formula (B.4):

|  |  |
| --- | --- |
|  | (B.4) |

where

|  |  |
| --- | --- |
|  | (B.5) |

and

|  |  |
| --- | --- |
|  | (B.6) |

When the following applies:

the orographic location factor, should be taken equal to 0.

1. leeward section for cliffs and escarpments Figure B.3:

For the ranges:

the orographic location factor, should be calculated from Formula (B.7)

|  |  |
| --- | --- |
|  | (B.7) |

where

|  |  |
| --- | --- |
|  | (B.8) |
|  | (B.9) |

and

|  |  |
| --- | --- |
|  | (B.10) |

For the range:

Interpolate between values for

when

should be used

when

should be taken

1. leeward section for hills and ridges Figure B.4:

For the ranges

the orographic location factor, should be calculated from Formula (B.11):

|  |  |
| --- | --- |
|  | (B.11) |

where

|  |  |
| --- | --- |
| A | should be taken from Formula (B.5) and |

|  |  |
| --- | --- |
|  | (B.12) |

When the following applies:

the orographic location factor, should be taken equal to 0.

NOTE Formulae (B.5) to (B.12) are polynomial curve fits to empirical data for simple orographic shapes.

* 1. Neighbouring structures

(1) If a building is near to another building more than twice as high as the average height of the neighbouring structures, as a first approximation, the design of any of those nearby structures may be based on the peak velocity pressure at height () above ground calculated from Formula (B.13) for different ranges of the distance ). Refer to Figure B.6 for a first approximation to .

|  |  |  |
| --- | --- | --- |
|  |  |  |
|  |  | (B.13) |
|  |  |  |

in which the radius *r* is:

if

if

NOTE The structural height , the radius , the distance and the dimensions and are illustrated in Figure B.5.

(2) Increased wind velocities may be disregarded when is more than half the height of the high building, i.e. .

NOTE The environment around a tall building can change during its design working life and this can change the wind loading on it and the surrounding buildings.

Ein Bild, das Diagramm, Entwurf, Zeichnung, technische Zeichnung enthält.

Automatisch generierte Beschreibung

Figure B.5 — Influence of a high-rise building, on two different nearby structures (1 and 2)

* 1. Displacement height

(1) Closely spaced buildings and other obstructions (typically found in Terrain Category IV) cause the wind to behave as if the ground level was raised to a displacement height, .

(2) may be determined by Formula (B.14), see Figure B.6.

|  |  |  |
| --- | --- | --- |
|  | is the lesser of or |  |
|  | is the lesser of or | (B.14) |
|  |  |  |

Ein Bild, das Diagramm, technische Zeichnung, Reihe, Entwurf enthält.

Automatisch generierte Beschreibung

Figure B.6 — Obstruction height and windward spacing

(2) The profile of peak velocity pressure at height, z may be lifted by a height *.*

(3) As these rules are direction dependant, the values of and should be established for each 30° sector as described in 6.3.2.

(4) In the absence of more accurate information, the obstruction height may be taken as for terrain category IV.

* 1. Alternative wind model
     1. General

(1) An alternative wind model for the global design of slender structures up to 300 m is described in the following clauses.

NOTE 1 Slender structures refers to lattice towers and guyed masts (see Annex J), tall chimneys, and any other structure where the height is more than 10 times the largest plan dimension.

NOTE 2 National Annexes can extend the applicability of the alternative wind model to other types of structures.

(2) To calculate the mean velocity and turbulence intensity up to , substitute B.8.2 for Clause 6.3.2 and substitute B.8.3 for 6.4 for all values of .

(3) Where the displacement height, , is significant, the height, , in B.8.2 and B.8.3 may be replaced with ().

* + 1. Terrain Roughness

(1) The roughness factor, , should account for the variability of the mean wind velocity at the site of the structure due to:

* the height above ground level
* the terrain roughness windward of the structure in the wind direction considered

NOTE 1 The procedure for the determination of the roughness factor at height is given by Formula (B.15), based on a modified logarithmic velocity profile, unless the National Annex gives a different procedure.

|  |  |  |  |
| --- | --- | --- | --- |
|  | for |  | (B.15) |
|  | for |  |  |

where

;

|  |  |
| --- | --- |
|  | is the roughness adjustment coefficient; |
|  | is the roughness length; |
|  | is the minimum height; |
|  | is to be taken as 300 m; |
|  | is the gradient height, defined as where is the Coriolis Parameter , and is the latitude of the site in degrees. This only applies for storm winds. |
|  | is the basic wind velocity calculated using Formula (6.1) |
|  | terrain factor depending on the roughness length calculated using Formula (6.7) |

NOTE 2 The values of , , and depend on terrain category. They are given in Table B.3 depending on five representative terrain categories unless the National Annex gives different values.

Table B.3 (NDP) — Roughness adjustment coefficients, roughness lengths and minimum heights

| Terrain category | |  |  |  |
| --- | --- | --- | --- | --- |
| m | m |  |
| 0 | Sea or coastal area exposed to the open sea | 0,003 | 1 | 1,28 |
| I | Lakes or flat and horizontal area with negligible vegetation and without obstacles | 0,01 | 1 | 1,17 |
| II | Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights | 0,05 | 2 | 1,00 |
| III | Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest) | 0,3 | 5 | 0,75 |
| IV | Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m | 1,0 | 10 | 0,55 |

(2) Formula (B.15) should not be used unless the upstream distance with uniform terrain roughness is long enough to stabilise the profile sufficiently, see 6.3.2(3).

NOTE is the ratio of the equilibrium mean wind speed at in the terrain category under consideration divided by the equilibrium mean wind speed at in terrain category II.

* + 1. Wind Turbulence

(1) The turbulence intensity at height should be taken equal to the standard deviation of the turbulence divided by the mean wind velocity.

(2) The determination of the turbulence intensity at height should be taken from Formula (B 1.7), based on a modified logarithmic velocity profile.

NOTE The National Annex can give an alternative procedure.

(3) The turbulent component of wind velocity has a mean value of zero and a standard deviation . The standard deviation of the turbulence may be determined using Formula (B.16).

|  |  |
| --- | --- |
|  | (B.16) |

(4) Values of turbulence intensity shall be calculated using Formula (B.17).

|  |  |  |  |
| --- | --- | --- | --- |
|  | for |  | (B.17) |
|  | for |  |  |

where

|  |  |
| --- | --- |
| and | should be taken from Table B.4; |
|  | is the orography factor as described in 6.3.3; |
|  | is the gradient height as described in B.8.2; |
|  | is the roughness length should be taken as defined in Table B.3. |

Table B.4 — Values of and

| Terrain category |  |  |
| --- | --- | --- |
| 0 | 2,10 | 70 |
| I | 2,15 | 55 |
| II | 2,30 | 35 |
| III | 2,45 | 25 |
| IV | 2,50 | 18 |

(5) For mean wind velocities lower than , stratified flow with zero turbulence should be considered for vortex-induced vibrations.

NOTE See Annex H for further guidance.

1. (normative)  
     
   Pressure coefficients for pressures on surface
   1. Use of this annex

(1) This Normative Annex contains additional provisions to 7.3(1) and 7.3(2) specifying pressure coefficients for external and internal pressures, respectively.

* 1. Scope and field of application

(1) This Normative Annex applies to buildings, cooling towers, chimneys, circular domes, silos and tanks.

(2) This Normative Annex gives loaded areas for many common forms of structures and their load carrying systems. For other forms of structure, the designer should consider different patterns of loading, taking account of influence lines, where appropriate.

(3) This clause should be used to determine the appropriate pressure coefficients for buildings, using:

* C.4 and C.5 for external pressures on buildings,
* C.6 for external pressures on circular buildings, towers, chimneys, domes, silos and tanks, C.7 for internal pressures.

NOTE External pressure coefficients give the effect of the wind on the external surfaces of structures; internal pressure coefficients give the effect of the wind on the internal surfaces of buildings.

(4) Friction coefficients should be determined for walls and surfaces following E.7.

* 1. Pressure and force coefficients
     1. Symmetric and counteracting pressures and forces

(1) If instantaneous fluctuations of wind over surfaces can give rise to significant asymmetry of loading and the structural form is likely to be sensitive to such loading (e.g. torsion in nominally symmetric single core buildings) then their effect should be taken into account.

NOTE If the National Annex does not provide other procedures, asymmetric loadings are given as follows:

1. For rectangular plan buildings that are susceptible to torsional effects the pressure distribution given in Figure C.1 should be applied for the representation of the torsional effects due to an inclined wind or due to lack of correlation between wind forces acting at different places on the structure.

Ein Bild, das Diagramm, Reihe, technische Zeichnung enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | zone D |
| 2 | zone E |

Figure C.1 — Pressure distribution used to take torsional effects into account — The zones and values for should be taken from Table C.2 and Figure C.7 Key

1. For other cases an allowance for asymmetry of loading should be made by completely removing the design wind action from those parts of the structure where its action will produce a beneficial effect.
2. Annex G provides further guidance.
   * 1. Effects of ice and snow on pressure and force coefficients

(1) Any changes in the reference area or shape owing to changes in the geometry of a structure due to ice or snow should be taken into account.

NOTE 1 Force coefficients for iced structures are given in E.7.

NOTE 2 Further information can be given in the National Annex.

* 1. Pressure coefficients for rectangular plan buildings
     1. General

(1) The external pressure coefficients for surfaces of buildings depend on the size of the loaded surface area , which is the area of the surface that produces the wind action in the section to be calculated. Two sets of external pressure coefficients are given which depend on size: detailed coefficients,, and local coefficients,.

(2) Detailed coefficients apply to loaded surface areas of 10 m2; they can be used to evaluate the actions on any structural member with a tributary loading area of 10 m2 or more.

(3) Local coefficients apply to loaded surface areas of 1 m2; they should be used for the design of small elements and fixings.

(4) Global coefficients are given to evaluate the actions on foundations and internal stiffening systems of the structure. They do not necessarily give the exact pressure distribution, but they give rise to simplified loading patterns, whose resultant is generally conservative. Global coefficients can be used when each of the surface areas of the structure contributing to the wind effect, are larger than 10 m2.

NOTE 1 Global external pressure coefficients are given in C.4. Other values can be given in the National Annex.

NOTE 2 The procedure for calculating external pressure coefficients for loaded areas between 1 m2 and 10 m2 based on external pressure coefficients and is given in Figure C.2.

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Automatisch generierte Beschreibung

The figure is based on the following:

|  |  |
| --- | --- |
| for | *A* |

Figure C.2 — Procedure for determining the external pressure coefficient for buildings with a loaded area between and

NOTE 1 The values of the external pressure coefficients provided conventionally refer to wind directions orthogonal to the building faces and represent the most unfavourable values obtained in a range of wind direction either side of the relevant orthogonal direction.

NOTE 2 The external pressure coefficients produce a load condition which is globally symmetric. The asymmetry of the load on the vertical surfaces arising when n θ≠0° is covered by Clause C.3.1(1). The asymmetry of the load on the roof surfaces arising when θ≠0° is accounted for by the large values of the pressure coefficients in zone F in C.5.3 through C.5.6.

(5) The length of the protrusion should be less than e⁄20, where 𝑒 should be taken as defined in Figure C.7. For larger lengths, see D.3.

(6) For protruding roof corners, the pressure on the underside of the roof overhang is equal to the pressure for the zone of the vertical wall directly connected to the protruding roof; the pressure on the top side of the roof overhang is equal to the pressure of the zone, defined for the roof. The rule is applicable to detailed coefficients and local coefficients.

NOTE National Annexes can provide additional guidance.

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Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | pressure on top side found from roof pressure |
| 2 | pressure on underside found from wall pressure |

Figure C.3 — Illustration of relevant pressures for protruding roofs

* + 1. Vertical walls

(1) For buildings where , the reference height for the windward face should be taken as equal to the building height , see Figure C.4.

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Automatisch generierte Beschreibung

Figure C.4 — Reference height for the windward face of buildings

(2) For buildings where , two zones should be specified for the evaluation of the reference height for the windward face. For the lower part of the building, up to height , the reference height . For the upper part of the building, i.e. for between and , the reference height should be selected by applying one of the two following criteria (Figure C.4):

1. The reference height is constant and equal to ; this simplifies the load scenario but gives larger forces.
2. The building is divided into strips of arbitrary height, each with a corresponding constant reference height, equal to the maximum height of the strip; this is a more complex loading pattern but gives lower forces.

(3) The reference height for leeward walls and for side walls should be taken equal to the height of the building for structures with . When , the reference height in Figure C.4 can be used for all walls.

(4) In the case of sloped roofs, the building height should be measured to the highest point of the roof.

(5) The global external pressure coefficients for the windward and leeward walls and for side walls of rectangular plan buildings should be as given in Table C.1 and Figure C.6.

(6) The global external pressures should be considered as acting simultaneously on all walls.

NOTE Other values can be given in the National Annex.

(7) The global external pressure coefficients should be taken from Table C.1 and shown in Figure C.6.

.

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Automatisch generierte Beschreibung

Figure C.5 — Geometry of rectangular plan buildings

Table C.1 — Global external pressure coefficients for rectangular plan buildings

| Windward wall | Side walls | Leeward wall |
| --- | --- | --- |
| :  : | :  : | :  : |

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Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | windward |
| 2 | leeward |
| 3 | side |

Figure C.6 — Global external pressure coefficients for rectangular plan buildings

NOTE For buildings with , the total wind loading can be based on the provisions given in E.1.2.

(8) The detailed and local external pressure coefficients and for zone A, B, C, D and E should be taken as defined in Figure C.7.

NOTE The values of and are given in Table C.2, depending on the ratio . For intermediate values of , linear interpolation can be applied. The values of Table C.2 also apply to walls of buildings with inclined roofs, such as duopitch and monopitch roofs.

Table C.2 — Detailed and local external pressure coefficients for vertical walls of rectangular plan buildings

| Zone | A | | B | | C | | D | | E | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  |  |  |  |
| 5 | −1,2 | −1,4 | −0,8 | −1,1 | −0,5 | | +0,8 | +1,0 | −0,7 | |
| 1 | −1,2 | −1,4 | −0,8 | −1,1 | −0,5 | | +0,8 | +1,0 | −0,5 | |
| ≤ 0,25 | −1,2 | −1,4 | −0,8 | −1,1 | −0,5 | | +0,7 | +1,0 | −0,3 | |

(9) In cases where the wind force on building structures is determined by application of the global pressure coefficients and cpe,10 on windward and leeward side (zones D and E) of the building simultaneously, the lack of correlation of wind pressures between the windward and leeward side may be taken into account.

(10) The lack of correlation of wind pressures between the windward and leeward side may be considered as follows:

* For buildings with the resulting force is multiplied by 1.
* For buildings with , the resulting force is multiplied by 0,85.
* For intermediate values of , linear interpolation can be applied.

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Automatisch generierte Beschreibung

a) Plan

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Automatisch generierte Beschreibung

b) Elevation for e < d

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Automatisch generierte Beschreibung

c) Elevation for e ≥ d

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Automatisch generierte Beschreibung

d) Elevation for e ≥ 5d

Key

|  |  |
| --- | --- |
| 1 | elevation |
| e | = b or 2h, whichever is smaller |

Figure C.7 — Key for vertical walls

* + 1. Flat roofs

(1) Flat roofs are defined as having a slope of

(2) The reference height for flat roofs should be taken as . The reference height for flat roofs with parapets should be taken as , being the height of parapet, see Figure C.8.

(3) The roof should be divided in zones, as shown in Figure C.8. These apply to the case of sharp eaves and can be conservative for other cases.

NOTE 1 The global external pressure coefficients are given in Table C.3 unless the National Annex gives different values.

Table C.3 (NDP) — Global pressure coefficients for flat roofs

|  |  |
| --- | --- |
| Zones F, G and H of Figure C.8 |  |
| Zone I of Figure C.8 |  |

In Zone I, where positive and negative values are given, both values should be considered.

The presence of parapets whose height exceeds 1/20 of the height of the building can lead to lower values of the detailed global and local pressure coefficient and , as specified in Table C.4.

(6) The detailed and local pressure coefficients and for zones F, G, H and I should be taken from Table C.4.

The resulting pressure coefficient on the parapet should be determined using D.2.

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Automatisch generierte Beschreibung

a) Parapets

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Automatisch generierte Beschreibung

b) Curved and mansard eaves

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Automatisch generierte Beschreibung

c) Plan view

Key

|  |  |
| --- | --- |
| 1 | edge of eave |
| *e* | = *b* or 2*h*, whichever is smaller |

Figure C.8 — Key for flat roofs

Table C.4 — Detailed and local external pressure coefficients for flat roofs

| Roof type | | Zone | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| F | | G | | H | | I | |
|  |  |  |  |  |  |  |  |
| Sharp eaves | | −1,8 | −2,5 | −1,2 | −2,0 | −0,7 | −1,2 | +0,2 | |
| −0,2 | |
| With Parapets |  | −1,6 | −2,2 | −1,1 | −1,8 | −0,7 | −1,2 | +0,2 | |
| −0,2 | |
|  | −1,4 | −2,0 | −0,9 | −1,6 | −0,7 | −1,2 | +0,2 | |
| −0,2 | |
|  | −1,2 | −1,8 | −0,8 | −1,4 | −0,7 | −1,2 | +0,2 | |
| −0,2 | |
| Curved Eaves |  | −1,0 | −1,5 | −1,2 | −1,8 | −0,4 | | +0,2 | |
| −0,5 | |
|  | −0,7 | −1,2 | −0,8 | −1,4 | −0,3 | | +0,2 | |
| −0,5 | |
|  | −0,5 | −0,8 | −0,5 | −0,8 | −0,3 | | +0,2 | |
| −0,5 | |
| Mansard Eaves |  | −1,0 | −1,5 | −1,0 | −1,5 | −0,3 | | +0,2 | |
| −0,5 | |
|  | −1,2 | −1,8 | −1,3 | −1,9 | −0,4 | | +0,2 | |
| −0,5 | |
|  | −1,3 | −1,9 | −1,3 | −1,9 | −0,5 | | +0,2 | |
| −0,5 | |
| * In Zone I, where positive and negative values are given, both values should be considered. * For mansard eaves with horizontal dimensions less than , the values for sharp eaves should be used. For the definition of e see Figure C.8. | | | | | | | | | |
| NOTE 1 For roofs with parapets or curved eaves, linear interpolation can be used for intermediate values of and .  NOTE 2 For roofs with mansard eaves, linear interpolation between , 45° and can be used. For linear interpolation between the values for and the values for flat roofs with sharp eaves can be used.  NOTE 3  For the mansard eave itself, the external pressure coefficients are given in Table C.11 “Detailed and local external pressure coefficients for duopitch roofs for .”, Zone F and G, depending on the pitch angle of the mansard eave.  NOTE 4 For the curved eave itself, the external pressure coefficients are given by linear interpolation along the curve, between values on the wall and on the roof. | | | | | | | | | |

* + 1. Monopitch roofs

(1) The reference height for monopitch roofs should be taken as , see Figure C.9.

(2) As for some slopes pressure can switch from negative to positive values, pressure coefficients with either signs should be taken into account.

(3) For a wind incidence perpendicular to the ridge, the global pressure coefficients should be taken from Table C.5 and Figure C.10.

NOTE The global external pressure coefficients are given in Table C.5 and shown in Figure C.10, unless the National Annex gives a different values.

(4) For a wind incidence parallel to the ridge, the roof should be divided in zones, and the global pressure coefficients should be taken from Table C.6 and Figure C.11

NOTE The global external pressure coefficients are given in Table C.6 and shown in Figure C.11 unless the National Annex gives a different values.

(5) The detailed and local pressure coefficients and for zones , , , and should be taken from Table C.7 and Table C.8, including protruding parts.

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Automatisch generierte Beschreibung

a) General eave to eave

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Automatisch generierte Beschreibung

b) Plan view — wind directions and

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Automatisch generierte Beschreibung

c) Plan view — wind direction

Key

|  |  |
| --- | --- |
| 1 | low eave |
| 2 | high eave |

Figure C.9 — Zoning (plan dimensions) for the detailed and local pressure coefficients on monopitch roofs. Zoning for global coefficient given in the respective tables

Table C.5 — Global external pressure coefficients for monopitch roofs; wind perpendicular to the eaves. corresponds to for

| Negative values | | Positive values | |
| --- | --- | --- | --- |
|  |  |  |  |
|  |  |  |  |
|  |  |  |  |
|  |  |  |  |

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Automatisch generierte Beschreibung

Figure C.10 — Global external pressure coefficients for monopitch roofs; wind perpendicular to the eaves — corresponds to for

Table C.6 — Global external pressure coefficients for monopitch roofs; wind parallel to the eaves

|  |  |  |
| --- | --- | --- |
| Zones , , and of Figure C.9 |  |  |
|  |  |
| Zone I of Figure C.9 |  |  |
|  |  |
|  |  |

Ein Bild, das Diagramm, Reihe enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | leeward zone |
| 2 | windward zone |

Figure C.11 — Global external pressure coefficients for monopitch roofs; wind parallel to the eaves

Table C.7 — Detailed and local external pressure coefficients for monopitch roofs for  = 0° and  = 180°

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Zone for wind direction | Pitch angle | Zone for wind direction  = 0° | | | | | |
| F | | G | | H | |
|  |  |  |  |  |  |
| **= 180°** | ‑75° | −0,5 | −1,0 | −0,5 | | −0,5 | |
| ‑60° | −0,5 | −1,0 | −0,5 | | −0,5 | |
| ‑45° | −0,6 | −1,3 | ‑0,5 | | −0,7 | |
| ‑30° | −1,1 | −2,3 | −0,8 | −1,5 | −0,8 | |
| ‑15° | −2,5 | −2,8 | −1,3 | −2,0 | −0,9 | −1,2 |
| ‑5° | −2,3 | −2,5 | −1,3 | −2,0 | −0,8 | −1,2 |
|  | | | | | | | |
| **= 0°** | 5° | −1,7 | −2,5 | −1,2 | −2,0 | −0,6 | −1,2 |
| 0,0 | | 0,0 | | 0,0 | |
| 15° | −0,9 | −2,0 | −0,8 | −1,5 | −0,3 | |
| +0,2 | | +0,2 | | +0,2 | |
| 30° | −0,5 | −1,5 | −0,5 | −1,5 | −0,2 | |
| +0,7 | | +0,7 | | +0,4 | |
| 45° | 0,0 | | 0,0 | | 0,0 | |
| +0,7 | | +0,7 | | +0,6 | |
| 60° | +0,7 | | +0,7 | | +0,7 | |
| 75° | +0,8 | | +0,8 | | +0,8 | |
| NOTE Linear interpolation for intermediate pitch angles can be used between values of the same sign. The values equal to 0,0 are given for interpolation purposes. | | | | | | | |

Table C.8 — Detailed and local external pressure coefficients for monopitch roofs for  = 90°

| Pitch angle | Zone for wind direction  = 90° | | | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Fup | | Flow | | G | | H | | I | |
|  |  |  |  |  |  |  |  |  |  |
| 5° | −2,1 | −2,6 | −2,1 | −2,4 | −1,8 | −2,0 | −0,6 | −1,2 | −0,5 | |
| 15° | −2,4 | −2,9 | −1,6 | −2,4 | −1,9 | −2,5 | −0,8 | −1,2 | −0,7 | −1,2 |
| 30° | −2,1 | −2,9 | −1,3 | −2,0 | −1,5 | −2,0 | −1,0 | −1,3 | −0,8 | −1,2 |
| 45° | −1,5 | −2,4 | −1,3 | −2,0 | −1,4 | −2,0 | −1,0 | −1,3 | −0,9 | −1,2 |
| 60° | −1,2 | −2,0 | −1,2 | −2,0 | −1,2 | −2,0 | −1,0 | −1,3 | −0,7 | −1,2 |
| 75° | −1,2 | −2,0 | −1,2 | −2,0 | −1,2 | −2,0 | −1,0 | −1,3 | −0,5 | |
| NOTE At (see table a)) the pressure changes rapidly between positive and negative values around a pitch angle of to , so both positive and negative values are given. For those roofs, two cases should be considered: one with all positive values, and one with all negative values. No mixing of positive and negative values is allowed on the same face. | | | | | | | | | | |

* + 1. Duopitch roofs

(1) The reference height for duopitch roofs should be taken as, see Figure C.12.

(2) For a wind incidence perpendicular to the ridge, the detailed and local pressure coefficients for the windward face (zones F, G and H of Figure C.12) should be taken as the same as those for a monopitch roof (see Table C.7 and Figure C.9).

(3) The global pressure coefficients for the leeward roof should be taken from Table C.9 and Figure C.13.

NOTE The global external pressure coefficients are given in Table C.9 and shown in Figure C.13, unless the National Annex gives different values.

(4) For a wind incidence parallel to the ridge, the roof should be divided in zones, and the global external pressure coefficients should be taken from Table C.10 and Figure C.14.

NOTE The global external pressure coefficients are given in Table C.10 and shown in Figure C.14 unless the National Annex gives different values.

(5) The detailed and local pressure coefficients and for zones F, G, H, J and I should be taken from Table C.11 and Table C.12, including protruding parts.

|  |  |
| --- | --- |
| Ein Bild, das Diagramm, Reihe, Entwurf, Zeichnung enthält.  Automatisch generierte Beschreibung | Ein Bild, das Diagramm, Reihe, Entwurf, technische Zeichnung enthält.  Automatisch generierte Beschreibung |
| Pitch angle positive | Pitch angle negative |

a) General

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Automatisch generierte Beschreibung

b) Plan view — wind direction

Ein Bild, das Diagramm, Reihe enthält.

Automatisch generierte Beschreibung

c) Plan view — wind direction

Key

|  |  |
| --- | --- |
| a | upwind face |
| b | downwind face |
| c | ridge or trough |

Figure C.12 — Zoning (plan dimensions) for the detailed and local pressure coefficients on duopitch roofs. Zoning for global coefficient given in the respective tables

Table C.9 — Global pressure coefficients for duopitch roofs; wind perpendicular to the ridge, leeward roof

|  |  |
| --- | --- |
|  |  |
|  |  |
|  |  |
|  | 3 |



Figure C.13 — Global pressure coefficients for duopitch roofs; wind perpendicular to the ridge, leeward face

Table C.10 — Global pressure coefficients for duopitch roofs; wind parallel to the ridge

|  |  |  |
| --- | --- | --- |
| Windward zone of depth equal to or , whichever is smaller (corresponding to zones F, G and H of Figure C.12): |  |  |
|  |  |
|  |  |
|  |  |
| Leeward zone (corresponding to zone I of Figure C.12) |  |  |
| and |  |
|  |  |

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Key

|  |  |
| --- | --- |
| 1 | downwind zone |
| 2 | upwind zone |

Figure C.14 — Global pressure coefficients for duopitch roofs; wind parallel to the ridge

Table C.11 — Detailed and local external pressure coefficients for duopitch roofs for

| Pitch angle | Zone for wind direction = 0° | | | | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| F | | G | | H | | I | | J | | |
|  |  |  |  |  |  |  |  |  |  | |
| −45° | −0,6 | | −0,6 | | −0,8 | | −0,7 | | −1,0 | −1,5 | |
| −30° | −1,1 | −2,0 | −0,8 | −1,5 | −0,8 | | −0,6 | | −0,8 | −1,4 | |
| −15° | −2,5 | −2,8 | −1,3 | −2,0 | −0,9 | −1,2 | −0,5 | | −0,7 | −1,2 | |
| −5° | −2,3 | −2,5 | −1,2 | −2,0 | −0,8 | −1,2 | −0,6 | | −0,6 | | |
| +0,2 | | +0,2 | | |
|  | | | | | | | | | | | |
| 5° | −1,7 | −2,5 | −1,2 | −2,0 | −0,6 | −1,2 | −0,6 | | −0,6 | | |
| 0,0 | | 0,0 | | 0,0 | | +0,2 | | +0,2 | | |
| 15° | −0,9 | −2,0 | −0,8 | −1,5 | −0,3 | | −0,4 | | −1,0 | | −1,5 |
| +0,2 | | +0,2 | | +0,2 | | 0,0 | | 0,0 | | 0,0 |
| 30° | −0,5 | −1,5 | −0,5 | −1,5 | −0,2 | | −0,4 | | −0,5 | | |
| +0,7 | | +0,7 | | +0,4 | | 0,0 | | 0,0 | | |
| 45° | 0,0 | | 0,0 | | 0,0 | | −0,2 | | −0,3 | | |
| +0,7 | | +0,7 | | +0,6 | | 0,0 | | 0,0 | | |
| 60° | +0,7 | | +0,7 | | +0,7 | | −0,2 | | −0,3 | | |
| 75° | +0,8 | | +0,8 | | +0,8 | | −0,2 | | −0,3 | | |
| NOTE 1 At the pressure changes rapidly between positive and negative values on the windward face around a pitch angle of  to +45°, so both positive and negative values are given. For those roofs, four cases should be considered where the largest or smallest values of all areas F, G and H are combined with the largest or smallest values in areas I and J. No mixing of positive and negative values is allowed on the same face.  NOTE 2 Linear interpolation for intermediate pitch angles of the same sign can be used between values of the same sign. (Do not interpolate between of  and of , but use the data for flat roofs in C.5.3). The values equal to 0,0 are given for interpolation purposes | | | | | | | | | | | |

Table C.12 — Detailed and local external pressure coefficients for duopitch roofs for = 90°

| Pitch angle | Zone for wind direction = 90° | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| F | | G | | H | | I | |
|  |  |  |  |  |  |  |  |
| –45° | –1,4 | –2,0 | –1,2 | –2,0 | –1,0 | –1,3 | –0,9 | –1,2 |
| –30° | –1,5 | –2,1 | –1,2 | –2,0 | –1,0 | –1,3 | –0,9 | –1,2 |
| –15° | –1,9 | –2,5 | –1,2 | –2,0 | –0,8 | –1,2 | –0,8 | –1,2 |
| –5° | –1,8 | –2,5 | –1,2 | –2,0 | –0,7 | –1,2 | –0,6 | –1,2 |
| 5° | –1,6 | –2,2 | –1,3 | –2,0 | –0,7 | –1,2 | –0,6 | |
| 15° | –1,3 | –2,0 | –1,3 | –2,0 | –0,6 | –1,2 | –0,5 | |
| 30° | –1,1 | –1,5 | –1,4 | –2,0 | –0,8 | –1,2 | –0,5 | |
| 45° | –1,1 | –1,5 | –1,4 | –2,0 | –0,9 | –1,2 | –0,5 | |
| 60° | –1,1 | –1,5 | –1,2 | –2,0 | –0,8 | –1,0 | –0,5 | |
| 75° | –1,1 | –1,5 | –1,2 | –2,0 | –0,8 | –1,0 | –0,5 | |

* + 1. Hipped roofs

(1) The reference height for hipped roofs should be taken as , see Figure C.15.

(2) For windward and leeward faces, the same global coefficients defined for duopitch roofs should be used (see C.4.5).

(3) For the side faces, the global pressure coefficients given in Table C.13 and Figure C.16 should be used.

NOTE The global external pressure coefficients are given in Table C.13 and shown in Figure C.16 unless the National Annex gives different values.

(4) The detailed and local pressure coefficients and for zones F, G, H, I, J, K, L, M and N should be taken from Table C.14, including protruding parts.

|  |  |
| --- | --- |
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| a) Wind direction *θ* = 0° | b) Wind direction *θ* = 90° |

Key

|  |  |
| --- | --- |
| *e* | =*b* or 2*h*, whichever is smaller |

Figure C.15 — Zoning (plan dimensions) for the detailed and local pressure coefficients on hipped roofs. Zoning for global coefficient given in the respective tables

Table C.13 — Global pressure coefficients for hipped roofs; side faces

|  |  |
| --- | --- |
|  |  |
|  |  |
|  |  |
|  |  |



Figure C.16 — Global pressure coefficients for hipped roofs; side faces

Table C.14 — Detailed and local external pressure coefficients for hipped roofs

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Pitch angle** for *θ*= 0°  for *θ*= 90° | **Zone for wind direction and** | | | | | | | | | | | | | | | | | |
| **F** | | **G** | | **H** | | **I** | | **J** | | **K** | | **L** | | **M** | | **N** | |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 5° | –1,7 | –2,5 | –1,2 | –2,0 | –0,6 | –1,2 | –0,3 | | –0,6 | | –0,6 | | –1,2 | –2,0 | –0,6 | –1,2 | –0,4 | |
| +0,0 | | +0,0 | | +0,0 | |
| 15° | –0,9 | –2,0 | –0,8 | –1,5 | –0,3 | | –0,5 | | –1,0 | –1,5 | –1,2 | –2,0 | –1,4 | –2,0 | –0,6 | –1,2 | –0,3 | |
| +0,2 | | +0,2 | | +0,2 | |
| 30° | –0,5 | –1,5 | –0,5 | –1,5 | –0,2 | | –0,4 | | –0,7 | –1,2 | –0,5 | | –1,4 | –2,0 | –0,8 | –1,2 | –0,2 | |
| +0,5 | | +0,7 | | +0,4 | |
| 45° | –0,0 | | –0,0 | | –0,0 | | –0,3 | | –0,6 | | –0,3 | | –1,3 | –2,0 | –0,8 | –1,2 | –0,2 | |
| +0,7 | | +0,7 | | +0,6 | |
| 60° | +0,7 | | +0,7 | | +0,7 | | –0,3 | | –0,6 | | –0,3 | | –1,2 | –2,0 | –0,4 | | –0,2 | |
| 75° | +0,8 | | +0,8 | | +0,8 | | –0,3 | | –0,6 | | –0,3 | | –1,2 | –2,0 | –0,4 | | –0,2 | |
| NOTE 1 At the pressures changes rapidly between positive and negative values on the windward face at pitch angle of  = +5° to +45°, so both positive and negative values are given. For those roofs, two cases should be considered: one with all positive values, and one with all negative values. No mixing of positive and negative values are allowed.  NOTE 2 Linear interpolation for intermediate pitch angles of the same sign can be used between values of the same sign. The values equal to 0,0 are given for interpolation purposes  NOTE 3 The pitch angle of the windward face always will govern the pressure coefficients. | | | | | | | | | | | | | | | | | | |

* + 1. Multispan roofs

(1) The reference height should be taken as the height of the structure, , see Figure C.17.

(2) Global and detailed pressure coefficients for wind directions 0°, 90° and 180° for each span of a multispan roof may be derived from the pressure coefficient for each individual span.

(3) Modifying factors for the global pressures for wind directions 0° and 180° on each span should be derived:

* from C.4.4 for monopitch roofs, modified for their position according to
* Figure C.17 a) and b).
* from C.2.5 for duopitch roofs for modified for their position according to
* Figure C.17 c) and d).

(4) For a multispan roof when no resulting horizontal forces arise, a minimum roughness factor of 0,05 (independently from the roughness of the structure) should be taken into account for wind actions normal to the areas of the multispan roof. Consequently, the minimum horizontal force perpendicular to or parallel with the eaves or ridges on a multispan roof at eaves or ridges height shall be taken from Formula (C.1):

|  |  |
| --- | --- |
|  | (C.1) |

where

|  |  |
| --- | --- |
|  | is the base area of each multispan roof; |
|  | is the peak velocity pressure at height . |

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Figure C.17 — Elevation - detailed pressure coefficients for multispan roofs

(5) In configuration two cases should be considered depending on the sign of pressure coefficient on the first roof.

NOTE In configuration c the first is the of the monopitch roof, the second and all following are the of the troughed duopitch roof.

* + 1. Vaulted roofs

(1) This Clause applies to vaulted roofs, rectangular in plan.

NOTE Pressure coefficients for vaulted roofs can be given in the National Annex; recommended values are provided below.

(2) The values of should be taken from Figure C.18 for different zones. The reference height should be taken as .

(3) In Figure C.18, zones A and C are equal to 1/4 of the total length of the roof; zone B is equal to 1/2 of the total length of the roof.

For zone A:

* for , is obtained by linear interpolation;
* for and , two values of have to be considered;
* the diagram is not applicable for flat roofs.



Figure C.18 — Detailed external pressure coefficients for vaulted roofs with rectangular plan

* + 1. Pressure on walls or roofs with more than one skin

(1) For buildings with walls or roofs with more than one skin the evaluation of the wind actions on principal structural members and on foundations, and those on structural member with a large tributary loading area (usually of more than 10 m2) should be carried out using the global and detailed external pressure coefficients (see C.4.1 to C.4.8, C.3, C.6.1 and C.6.3), and the internal pressure coefficients (see C.5) applying to buildings with one skin.

(2) This Clause gives criteria for the evaluation of the wind actions on each skin of multiple skin walls or roofs, for the purpose of the design of the skin itself and of its bearing members.

NOTE 1 Examples of skins are:

* for façades: claddings (outside skins), facings (inside skins);
* for roofs: loose-laid insulation boards (outside skins), ceilings (inside skins).

NOTE 2 The National Annex can provide additional guidance for the wind effects on each skin of external walls and roofs with more than one skin.

(3) As a first approximation the following rules can be applied:

* The permeability of a skin is defined as the ratio of the total area of the opening to the total area of the skin. A skin is defined as permeable if the value is larger than 0,1 %.
* The wind pressure on the less permeable skin may be taken as the difference between the internal and the external pressures.
* The wind force on a permeable outside or inside skin with approximately uniformly distributed openings may be calculated from the Formula (C.2) when the extremities of the layer between the skins are closed (Figure C.19 a)):

|  |  |
| --- | --- |
|  | (C.2) |

in which is the pressure equalization coefficient, and where is either or .

The values should be taken as:

for overpressure;

for underpressure.

NOTE Different values for *c*eq can be given in the National Annex.

If entries of air put the layer of air into communication with faces of the building other than the face on which the wall is situated (Figure C.19b)), these rules are not applicable.

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a) Extremities of the layer between the skins closed

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b) Extremities of the layer between the skins open

Figure C.19 — Corner details with two skins

In zones A of façades (see C.4.2) or zones F of roofs (see C.4.3 to C.4.7), where vortices can create small but sharp non-linear pressure gradients, larger net loads may be exerted locally.

* 1. Pressure coefficients for irregular buildings
     1. General

(1) The distribution of external pressure on buildings depends significantly on their geometry. Therefore, for buildings other than those with a rectangular plan and uniform height (see C.2), care must be taken in selecting external pressure coefficients.

(2) For buildings with a complex plan geometry, as for those with non-uniform height, pressure coefficients cannot be quantified in a simple manner; in these cases, their assessment may require wind tunnel testing.

NOTE External pressure coefficients for irregular buildings can be given in the National Annex; recommended values are given in C.3.

(3) This subclause deals with two particular types of irregular building. Subclause C.5.2 refers to buildings of uniform height having a plan which is a combination of rectangular elements. Subclause C.5.3 refers to buildings having a rectangular plan but made of elements of different height or recessed bodies.

(4) The aerodynamic behaviour is governed by the parameter , see Figure C.7.

(5) Recessed corners and bays less than can be ignored in the assessment of the pressure distribution around the building.

NOTE In the case of recessed corners and bays less of more than , reference can be made to the criteria given in the following Clauses.

* + 1. Buildings with non-rectangular plan

(1) This Clause applies to the cases of Figure C.20 and Figure C.21 and provides criteria for choosing the appropriate values for the detailed external pressure coefficients.

NOTE The zoning of the detailed external pressure coefficients are shown in Figure C.20 and Figure C.21 unless the National Annex gives different values.

(2) If the plan of the building comprises a body with a rectangular plan (generally of larger dimensions) from which other rectangular bodies protrude on the windward face (generally of smaller dimensions as in cases a, b and c in Figure C.20), the following rules apply. From the windward corner of the building from which the flow separates, 45° angle lines are drawn with respect to the direction of the oncoming flow. The surfaces inside the sector identified by these lines can be broken down into two zones: the first, indicated as X, belongs to body A (with parameters and ) from which the lines were plotted; the second, indicated as Y, belong to the rest of the building (body B, with geometric parameters and ).

(3) In the X zones, the pressure coefficient is the same as it would be in the absence of body B.

(4) In the Y zones, both the following situations are considered:

1. the pressure coefficient is the same as that in X zones of body A (and therefore generally negative);
2. the pressure coefficient is the same as that which would act on body B in the absence of body A (therefore generally positive).

(5) In all other areas of body B, pressure coefficients are the same as they would be in the absence of body A.

(6) If the ground plan of the building has recessed bays (case d in Figure C.20), geometric parameter , should be taken as equal either to or , whichever is smaller:

(7) If the recess dimensions (*b*1 and *d*1) do not exceed the value of :

* on the faces of the recess (indicated as X), the pressure should be taken as equal to that of the adjacent portion of the wall;
* on the other faces of the building, the pressure coefficient is the same as it would be in the absence of the recess.

(8) If the dimensions of the recess are more than , reference should be made to specific data or wind tunnel tests.

(9) For Y-shaped buildings the global external pressure coefficients should be taken from Figure C.21.



Figure C.20 — Key for non-rectangular plan buildings

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Figure C.21 — Detailed external pressure coefficients for Y-shaped buildings

* + 1. Buildings with non-uniform height

(1) For the cases of Figure C.22 the following criteria apply.

NOTE The zoning of external pressure coefficients are shown in Figure C.22, unless the National Annex gives different values.

(2) If the lower portion of the building is located leeward (Figure C.22 a) and b), the side walls of the building are divided into zones of uniform pressure coefficient. The pressure coefficients on the windward part of the taller portion are the same as they would be in the absence of the lower portion. The pressure coefficients on the leeward portions of the taller body and the lower body should be calculated with reference to the maximum height and to the longitudinal dimension of the building, following C.5.2. The geometric parameter , where is the cross wind dimension and is given in Figure C.22.

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Figure C.22 — Buildings with a rectangular plan and non-uniform height

(3) If the lower portion of the building is located windward (Figure C.22 c and d), the side walls of the building are divided in zones of uniform pressure coefficient in accordance with geometric parameters and , where and are the width exposed to the wind of the upper and lower portions of the building, respectively. The reference heights for each of the two zones are and .

(4) The pressure on the windward face of the lower portion of the building is calculated as if the taller portion were not present. The pressure on the windward and leeward faces of the taller portion is calculated as if the lower body were not present.

(5) For the cases of Figure C.23, the following criteria apply.

(6) The geometric parameters and are defined.

(7) When the upper portion of the building is at a distance from the windward face of the lower building more than (Figure C.23 a)), the pressure coefficients for the upper portion of the building are the same as they would be for a rectangular building of uniform height with base located at the level of the roof of the lower portion of the actual building. The reference height is the total height of the building .

(8) When the upper portion of the building is at a distance from the windward face of the lower building less than (Figure C.23 b)), the same criterion of clause (7) applies, except for the fact that a further zone is considered (zone P), in which a pressure coefficient should be used.

(9) The pressure coefficients on the roof of the lower portion of the building are the same as they would be in the absence of the upper portion of the building, except for an area of width (Figure C.23) around the upper portion of the building. In this area, the pressure coefficients are the same as those acting on the adjacent vertical walls of the upper portion of the building.



Figure C.23 — Pressure distribution on the roof of a building with non-uniform height

* 1. Pressure coefficients for circular structures
     1. Circular structures with vertical walls

(1) The following clauses apply to circular cylindrical structures such as towers, chimneys, silos and tanks, as well as circular buildings, with the exception of claddings, fixings and elements other than structural. They may also be applied in the case of walls deviating from the vertical by less than 5°.

(2) For cooling towers, see specific provisions in C.6.1.1.

(3) For silos and tanks, see specific provisions in C.6.1.2.

(4) For domes, see C.6.2 with vertical walls.

(5) Pressure for plan structures depend upon the Reynolds number defined by Formula (C.3).

|  |  |
| --- | --- |
|  | (C.3) |

where

|  |  |
| --- | --- |
|  | is the diameter; |
|  | is the kinematic viscosity of air (); |
|  | is the mean wind velocity at height . |

(6) For structures where , the reference height should be taken as equal to the structure height (Figure C.4).

(7) For structures where , two zones are specified. For the lower part of the structure, up to height , the reference height . For the upper part of the structure, i.e. for between and , the reference height should be selected by applying one of the two following criteria (Figure C.4):

1. The reference height is constant and equal to ; this simplifies the load scenario but gives larger forces.
2. The building is divided into strips of arbitrary height, each with a corresponding constant reference height, equal to the maximum height of the strip; this is a more complex loading pattern but gives lower forces.

(8) The external pressure coefficients of circular plan structures should be determined from Formula (C.4):

|  |  |
| --- | --- |
|  | (C.4) |

where

|  |  |
| --- | --- |
|  | is the external pressure coefficient without free-end flow (see (8)); |
|  | is the end-effect factor (see (8)). |

(9) The external pressure coefficient should be determined from the Formula (C.5) to (C.7), also plotted in Figure C.20.

|  |  |  |
| --- | --- | --- |
|  | for | (C.5) |
|  | for | (C.6) |
|  | for | (C.7) |

(10) The parameters appearing in Formula (C.5) to (C.7) should be taken from Table C.15 for various values of the Reynolds number. Interpolation is not allowed.

(11) The end-effect factor is given by Formula (C.8).

|  |  |
| --- | --- |
|  | (C.8) |

where

|  |  |
| --- | --- |
|  | is the end-effect factor (see Figure E.13). |

NOTE 1 Intermediate values can be interpolated linearly.

NOTE 2 Typical values in the above Figure are shown in Table C.15. Figure and Table are based on the Reynolds number with and given in 4.5.

NOTE 3 The above Figure is based on an equivalent roughness less than . Typical values of roughness height *k* are given in Table E.2.

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Figure C.24 — Pressure distribution for circular structures for different Reynolds number ranges and without end-effects

Table C.15 — Typical values for the pressure distribution for circular structures for different Reynolds number ranges and without end-effects

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  |  |  |
| 5·105 | 85 | −2,2 | 135 | −0,4 |
| 2·106 | 80 | −1,9 | 120 | −0,7 |
| 107 | 75 | −1,5 | 105 | −0,8 |
| where  is the angular distance in a horizontal cross-section from the stagnation line, expressed as circumferential angle in degrees;  is the position of the minimum pressure in degrees;  is the value of the minimum pressure coefficient;  is the position of the flow separation in degrees (see Figure C.24);  is the base pressure coefficient. | | | | |

* + 1. Walls of cooling towers

(1) The wind load is to be indicated as a characteristic load with a return period of 50 years and is to be applied at the full velocity pressure, independently of its direction.

NOTE Wind loads for walls of cooling towers can be given in the National Annex; recommended values are given in C.6.2.

(2) The influence of the wind direction may be taken into account in the determination of the wind load if secured statistical values on the wind rosette are available.

(3) The wind pressure distribution is influenced by the roughness of the cooling tower surface. The roughness is created by ribs which can generally be implemented as pilaster strips for the climbing formwork and/or as additional wind ribs.

(4) The external pressure is calculated as

|  |  |
| --- | --- |
|  | (C.9) |

where

|  |  |
| --- | --- |
|  | height above ground; |
|  | external pressure coefficient determined according to Figure C.26 and Table C.17. |
|  | gust velocity pressure; |
|  | dynamic amplification factor determined according to Figure C.27; |
|  | interference factor determined according to Figure 28. |

The internal pressure is calculated as

|  |  |
| --- | --- |
|  | (C.10) |

where

|  |  |
| --- | --- |
|  | gust velocity pressure according to Clause 4 at height (see Figure C.27); |
|  | internal pressure coefficient. |

NOTE The National Annex can provide additional guidance.

(5) The size factor cannot be applied.

(6) The internal pressure is assumed to be constant over the full height and circumference of the cooling tower shell. It is negative (suction). The internal pressure coefficient .

(7) The basis for the distribution of the wind load in the circumferential direction is the six standardized pressure distribution curves as presented in Figure C.26 and Table C.17: K 1,0 – K 1,1 – K 1,2 – K 1,3 – K 1,5 – K 1,6

(8) The input parameter for the pressure distribution curves is the surface roughness parameter according to Figure C.25 and Table C.16 with the average distance between the ribs and the average height of the ribs taken at one-third of the shell height.

(9) Surfaces are considered to have an off-shutter finish if uniformly distributed roughness dents with average heights greater than 5 ∙ 10‑5 times the average diameter of the shell occur. In the case of a smooth surface, pressure distribution curve K 1.6 is to be used. Each of the curves is described by three analytical functions (Figure C.25). For comparison, Table C.16 additionally presents the aerodynamic force coefficient (resistance coefficient) for the resulting wind force.

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|  |  |
| --- | --- |
| 1 | *h*R - average height of the ribs |
| 2 | *a*R – average distance of the ribs |

Figure C.25 — Pressure minimums for external pressure in relation to surface roughness

Table C.16 — Pressure minimums and associated pressure distribution curves for external pressure in relation to surface roughness

| Surface | Roughness parameter | Pressure minimum | Distribution curve |
| --- | --- | --- | --- |
|  |  |
| With ribs | 0,025 … 0,100 | ‑1,0 | K 1,0 |
| 0,016 … 0,025 | ‑1,1 | K 1,1 |
| 0,010 … 0,016 | ‑1,2 | K 1,2 |
| 0,006 … 0,010 | ‑1,3 | K 1,3 |
| Without ribs | Off-shutter finish smooth | ‑1,5 | K 1,5 |
| ‑1,6 | K 1,6 |

(10) Dynamic amplification: Resonant vibrations caused by the fluctuating wind load component are taken into account by increasing the equivalent static load. The dynamic amplification factor for shells with and without stiffening rings can be taken from Figure C.27, where designates the lowest natural frequency of the shell including the supports and the foundation. The dynamic amplification factor has been calculated for the maximum tensile forces in the lower third of the shell height using numerical methods. This may be considerably larger for membrane forces in other parts of the shell and for bending moments. Related experience indicates, however, that a uniform amplification factor as given in Figure C.27 is, in general, adequate. For unusual shell geometries and for more detailed investigations, a calculation in accordance with the theory of random vibrations can be made based on detailed acquisition of the stochastic dynamic behaviour with random dynamic wind load.

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|  |  |
| --- | --- |
| 1 | location of minimum cpe value for curve K1,5, for numerical values of and refer to Table C.17 |

Figure C.26 — Pressure distribution curves

Table C.17 — Pressure distribution curves by areas and corresponding wind resistance coefficients

| **Curve** | **Pressure min.** | **Range of** | | |  |
| --- | --- | --- | --- | --- | --- |
| K 1,0 | ‑1,0 |  |  | ‑0,5 | 0,66 |
| K 1,1 | ‑1,1 |  |  | ‑0,5 | 0,64 |
| K 1,2 | ‑1,2 |  |  | ‑0,5 | 0,60 |
| K 1,3 | ‑1,3 |  |  | ‑0,5 | 0,56 |
| K 1,5 | ‑1,5 |  |  | ‑0,5 | 0,49 |
| K 1,6 | ‑1,6 |  |  | ‑0,5 | 0,46 |

(11) Interference effects: If further cooling towers or high power plant buildings are in close vicinity to the cooling tower under consideration, their flow fields will interfere with each other, altering the static and dynamic wind load as compared to a free-standing tower. Consequently, increased stresses can occur, depending on the type and distance of the adjacent buildings. The interference effects are taken into account by increasing the wind load (equivalent static load) for the free-standing tower by an interference factor FI. The amplified wind load has to be taken into account for the design of the tower and the supporting structure including the foundation, but not for the proofs of the subsoil.

Ein Bild, das Diagramm, Reihe, technische Zeichnung, Plan enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | *d*T –diameter at the throat height |
| 2 | *h* – complete height of the supports and the shell |
| 3 | Local height above ground |
| *n*min | lowest natural frequency of the shell including the supports and the foundation |

Dimensions: in kN/m²; in 1/s; , in m.

Figure C.27 — Dynamic amplification factor

(12) The interference factor is determined considering the distance parameter and the type of the adjacent buildings. The distance parameter for cooling tower — cooling tower interference is shown in Figure C.28 and for cooling tower — building interference in Figure C.29.

The average diameter of the shell should be calculated from Formula (C.11):

|  |  |
| --- | --- |
|  | (C.11) |

where

|  |  |
| --- | --- |
|  | diameter at the lower edge of the shell; |
|  | diameter at the throat height. |

(13) If the distance parameter is greater than the upper limit value , then . If is smaller than the lower limit , no interference factor is specified, because in this case a global amplification of the wind load cannot be adequately applied. In this case more detailed investigations are recommended, e. g. wind tunnel tests in a boundary layer wind tunnel. If , the interference factor and the increase in the minimum reinforcement ratio in the circumferential direction are to be determined as described below. Figure C.28 applies to cooling tower — cooling tower interference. The limit values are and . The interference factor is also valid for groups of more than two cooling towers.

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Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | neighbouring cooling tower |
| 2 | cooling tower under consideration |

Figure C.28 — Cooling tower — cooling tower interference (left)

Ein Bild, das Diagramm, Entwurf, technische Zeichnung, Reihe enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | building |
| 2 | cooling tower under consideration |
| 3 | no influence (FI=1,0) |
| 4 | estimation of FI after formula (C.12) |
| 5 | no regulation possible, more detailed investigation, e.g. wind tunnel experiments, required |

Figure C.29 — Cooling tower — building interference: Definition of distance parameter , upper distance limit , lower distance limit

(14) Figure C.29 applies to cooling tower — building interference. An interference factor may be neglected if the building height is less than 40 % of the cooling tower height. The interference factor FI may be calculated after determination of and in accordance with Figure C.29 by the following Formula (C.12):

|  |  |
| --- | --- |
|  | (C.12) |

(15) If the cooling tower is surrounded by several groups of tall buildings, a more detailed examination of the interference effects is necessary. If there is more than one interference situation, the most critical case is to be considered. The interference factors may be disregarded if the static and dynamic effects of interference are investigated in more detail. In this case the influence of the wind rosette (i.e. the direction-related influence) can be taken into account.

* + 1. Domes

(1) This Clause applies to circular domes.

NOTE Unless otherwise specified in the National Annex, the values of are given in Figure C.30 for different zones.

The reference height should be taken as .



NOTE is constant along arcs of circles, intersections of the sphere and of planes perpendicular to the wind; it can be determined as a first approximation by linear interpolation between the values in A, B and C along the arcs of circles parallel to the wind. In the same way the values of in A if and in B or C if can be obtained by linear interpolation in the Figure above.

Key

|  |  |
| --- | --- |
| 1 | *C*pe,10constant along plane |

Figure C.30 — Values of detailed external pressure coefficients for circular domes

* + 1. Circular silo and tank structures

(1) The distribution of wind pressures around a squat circular silo or ground-supported tank (see Figure C.31) may be important to the assessment of anchorage requirements and wind buckling resistance. Values given in C.6.1 may not provide enough detail in certain cases.

NOTE Unless otherwise specified in the National Annex, the values of are given in Figure C.32, Figure C.33 and Figure C.34. The pressure variation around an isolated silo can be defined in terms of the circumferential coordinate as defined in Figure C.32 and Figure C.33.

(2) The circumferential variation of the pressure distribution (positive inward) on an isolated closed roof silo (see Figure C.32) should be taken from Formula (C.13):

|  |  |
| --- | --- |
|  | (C.13) |

where dc is the diameter of the silo and *h* its overall height (is the aspect ratio for the complete structure and its supports) (see Figure C.31). For silos with greater than 0,50, the values for should be adopted. The pressure distribution should not be based on the cylinder height .

Ein Bild, das Diagramm, technische Zeichnung, Reihe, Entwurf enthält.

Automatisch generierte Beschreibung

Figure C.31 — Wind loaded silo

Ein Bild, das Diagramm, Reihe enthält.

Automatisch generierte Beschreibung

1. Figure C.32 — Wind pressure variation around half circumference in isolated silo.

(3) The circumferential variation of the pressure distribution (positive inward) on a closed roof silo in a group Figure C.33 may be taken as:

|  |  |
| --- | --- |
|  | (C.14) |

where the ratio of the separation, s, to the diameter, , is less than or equal to 3,0.

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Automatisch generierte Beschreibung

1. Figure C.33 — Wind pressure variation around half circumference of silo in group.

(4) Internal pressure coefficients should be taken from C.7.

(5) Where there is a catch basin, the external pressure on the tank shell may be assumed to reduce linearly with height, see Figure C..

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Automatisch generierte Beschreibung

Figure C.34 — Pressure distribution for wind loading on a circular cylindrical tank with a catch basin

(6) Reduced wind loads may be used for erection situations in accordance with EN 1991‑1‑6.

* 1. Internal pressures

(1) The internal pressure coefficient, , depends on the size and distribution of the openings in the building envelope. Internal and external pressures shall be considered to act at the same time. The worst combination of external and internal pressures shall be considered for every combination of possible openings and other leakage paths. The internal pressure coefficient can be used in combination with global, detailed global and local external pressure coefficients. This applies to buildings with and without internal partitions.

(2) The reference height for the internal pressures should be equal to the reference height for the external pressures on the faces which contribute by their openings to the creation of the internal pressure. If there are several openings the largest value of should be used to determine .

(3) For buildings where the only openings originate from the background permeability, or for buildings with evenly distributed openings of similar size, then should be taken as the more onerous of +0,2 and –0,3 for exterior walls and roof. For internal partition walls the net pressure coefficient can be taken as ±0,4.

NOTE 1 Background permeability the effect of unintended or intended, distributed leakage of the façade finishing is typically in the range 0,01 % to 0,1 % of the face area. Reference values are given in Table C.18.

NOTE 2 Evenly distributed openings of similar size can be small openings such as doors, windows, ventilators, chimneys etc.

(4) When, in at least two sides of the building (facades or roof) without partitions, the total area of openings on each side is more than 30 % of the area of that side, the actions on the structure should not be calculated from the rules given in this Clause but the rules of D.3 and D.4 should instead be used.

Table C.18 — Typical permeability of constructions

|  | Permeability |
| --- | --- |
| Office: curtain walling |  |
| Office: internal partition walling |  |
| Housing: regular |  |
| Housing: energy efficient housing |  |

(5) A face of a building should be regarded as dominant when the area of openings at that face is at least twice the area of openings and leakages in the remaining faces of the building considered.

(6) For a building with a functioning requiring a dominant face, the internal pressure should be taken as a fraction of the external pressure at the openings of the dominant face. The values given by formulae (C.5) and (C.6) should be used.

When the area of the openings at the dominant face is twice the area of the openings in the remaining faces:

|  |  |
| --- | --- |
|  | (C.15) |

When the area of the openings at the dominant face is at least 3 times the area of the openings in the remaining faces:

|  |  |
| --- | --- |
|  | (C.16) |

where is the value for the external pressure coefficient at the openings in the dominant face. When these openings are located in zones with different values of external pressures an area weighted average value of should be used.

When the area of the openings at the dominant face is between 2 and 3 times the area of the openings in the remaining faces linear interpolation may be used to calculate .

NOTE Examples of buildings where one or more openings can make the face dominant include hospitals, fire stations and large warehouses, because of their function.

(7) Where an external opening, such as a door or a window, would be dominant when open but is considered to be closed in the ultimate limit state, during severe windstorms, the condition with the door or window open may be considered as an accidental design situation in accordance with EN 1990.

NOTE 1 Checking of the accidental design situation is important for tall internal walls (with high risk of hazard) when the wall has to carry the full external wind action because of openings in the building envelope.

NOTE 2 The National Annex can provide additional guidance.

(8) For buildings without a dominant face, and where the openings are permanent but do not meet the requirements of C.7(3), the internal pressure coefficient could be determined from Formula (C.17):

|  |  |
| --- | --- |
|  | (C.17) |

where

|  |  |
| --- | --- |
|  | is the total area of openings on surfaces with a positive external pressure coefficient; |
|  | is the total area of openings on surfaces with a negative external pressure coefficient; |
|  | is the space averaged external pressure coefficient for openings subject to positive external pressure; |
|  | is the space averaged external pressure coefficient for openings subject to negative external pressure. |

The space averaged external pressure coefficients are given by Formulae (C.18) and (C.19):

|  |  |
| --- | --- |
|  | (C.18) |
|  | (C.19) |

where

|  |  |
| --- | --- |
|  | is the area of the *j*-*th* opening with a positive external pressure coefficient; |
|  | is the area of the *j*-th opening with a negative external pressure coefficient; |
|  | is the external pressure coefficient of the *j*-th opening subject to positive external pressure; |
|  | is the external pressure coefficient of the *j*-th opening subject to negative external pressure. |

(9) The internal pressure coefficient of open silos and chimneys should be based on Formula (C.20):

|  |  |
| --- | --- |
|  | (C.20) |

The internal pressure coefficient of vented tanks with small openings should be based on Formula (C.21):

|  |  |
| --- | --- |
|  | (C.21) |

The reference height should be taken as equal to the height of the structure.

As an alternative the value shall also be used if it produces the worst load condition.

(10) The internal pressure coefficient of circular structures with openings at the bottom and at the top, e.g. cooling towers, should be based on Formula (C.22):

|  |  |
| --- | --- |
|  | (C.22) |

1. (normative)  
     
   Net pressure and force coefficients for walls, roofs and skins
   1. Use of this annex

(1) This Normative Annex contains additional provisions to 7.4 and 7.5 specifying net pressure coefficients and force coefficients, respectively.

* 1. Scope and field of application

(1) This Normative Annex applies to canopy roofs, porches, balconies, free-standing walls, parapets, fences and signboards.

* 1. Net pressure and force coefficients for canopy roofs, porches and balconies
     1. General

(1) A canopy roof is defined as the roof of a structure that does not have permanent walls, such as petrol stations, Dutch barns, etc.

(2) The global force coefficient should be used for evaluation of the resulting force on the canopy. It should be used in the design of the columns and the foundations. The net pressure coefficient represents the maximum local pressure for all wind directions. It should be used in the design of roofing elements and fixings.

(3) The degree of blockage under a canopy roof is shown in Figure D.1 should be described by the blockage , which is the ratio of the area of feasible, actual obstructions under the canopy divided by the cross sectional area under the canopy, both areas being normal to the wind direction.

NOTE represents an empty canopy, and represents the canopy fully blocked with contents to the leeward eaves only (this is not a closed building).

(4) For canopies with double skins, the impermeable skin and its fixings should be calculated with and the permeable skin and its fixings with .

(5) Friction forces should be considered (see E.8).

(6) The reference height should be taken as as shown in Figure D.3 and Figure D.6.

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Automatisch generierte Beschreibung

Figure D.1 — Airflow over canopy roofs

* + 1. Monopitch canopies

(1) For a wind incidence perpendicular to the ridge, the global force coefficients for monopitch canopies should be taken form Table D.1 and Figure D.2. For intermediate values of the force coefficients may be obtained by linear interpolation between the cases and .

NOTE The force coefficients are given in Table D.1 and shown in Figure D.2 unless the National Annex provides different values.

Table D.1 — Force coefficients for monopitch canopies

|  |  |  |
| --- | --- | --- |
| Positive values | Aggll values of |  |
| Negative values |  |  |
|  |  |

Ein Bild, das Text, Reihe, Diagramm, parallel enthält.

Automatisch generierte Beschreibung

Figure D.2 — Force coefficients for monopitch canopies

(2) The worst load cases among those shown in Figure D.3 should be considered, in which the resultant force is applied at from the windward edge.

(3) For a wind incidence parallel to the ridge, the global force coefficients of Table D.1 and Figure D.2 for should be used.

(4) The net pressure coefficients for monopitch canopies should be taken from Table D.2 with reference to Figure D.4 for and , and take account of the combined effect of wind acting on both the upper and lower surfaces of the canopies for all wind directions. Intermediate values may be found by linear interpolation.

(5) Leeward of the position of maximum blockage, values for should be used.

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Figure D.3 — Definition of direction and location of the resultant force for monopitch canopies

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Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | high eave |
| 2 | low eave |

Figure D.4 — Key and plan for monopitch canopies

Table D.2 — values for monopitch canopies

|  | Blockage | Net pressure coefficient | | |
| --- | --- | --- | --- | --- |
| A | B | C |
| 0° | Maximum, all values of | +0,5 | +1,8 | +1,1 |
| Minimum, | −0,6 | −1,3 | −1,4 |
| Minimum, | −1,5 | −1,8 | −2,2 |
| 5° | Maximum, all values of | +0,8 | +2,1 | +1,3 |
| Minimum, | −1,1 | −1,7 | −1,8 |
| Minimum, | −1,6 | −2,2 | −2,5 |
| 10° | Maximum, all values of | +1,2 | +2,4 | +1,6 |
| Minimum, | −1,5 | −2,0 | −2,1 |
| Minimum, | −2,1 | −2,6 | −2,7 |
| 15° | Maximum, all values of | +1,4 | +2,7 | +1,8 |
| Minimum, | −1,8 | −2,4 | −2,5 |
| Minimum, | −1,6 | −2,9 | −3,0 |
| 20° | Maximum, all values of | +1,7 | +2,9 | +2,1 |
| Minimum, | −2,2 | −2,8 | −2,9 |
| Minimum, | −1,6 | −2,9 | −3,0 |
| 25° | Maximum, all values of | +2,0 | +3,1 | +2,3 |
| Minimum, | −2,6 | −3,2 | −3,2 |
| Minimum, | −1,5 | −2,5 | −2,8 |
| 30° | Maximum, all values of | +2,2 | +3,2 | +2,4 |
| Minimum, | −3,0 | −3,8 | −3,6 |
| Minimum, | −1,5 | −2,2 | −2,7 |

* + 1. Duopitch canopies

(1) For a wind incidence perpendicular to the ridge, the global force coefficients for duopitch canopies should be taken from Table D.3 and Figure D.5 for . For intermediate values of the force coefficients may be obtained by linear interpolation between the cases and .

NOTE The force coefficients are given in Table D.3 and shown in Figure D.5 unless the National Annex provides different values.

Table D.3 — Force coefficients for duopitch canopies

|  |  |  |  |
| --- | --- | --- | --- |
| Positive values of (ridge roof) | All values of |  | |
| Negative values of (trough roof) |  |  |  |
|  |  |
|  | all values of |  |

Ein Bild, das Text, Diagramm, Reihe, parallel enthält.

Automatisch generierte Beschreibung

Figure D.5 — Force coefficients for duopitch canopies

(2) The worst load cases among those shown in Figure D.6 should be considered; where two forces are shown, they shall be taken as acting simultaneously.

(3) For a wind incidence parallel to the ridge, the global net pressure coefficients of Table D.1 and Figure D.2 for should be used.

(4) The net pressure coefficients for duopitch canopies should be taken from Table D.4 and Table D.5 with reference to Figure D.7, for and , and take account of the combined effect of wind acting on both the upper and lower surfaces of the canopies for all wind directions. Intermediate values may be found by linear interpolation.

(5) Leeward of the position of maximum blockage, values for should be used.



Figure D.6 — Location of the centre of force for duopitch canopies



Figure D.7 — Key and plan for duopitch canopies

Table D.4 — values for duopitch canopies for > 0°

|  | Blockage | Net pressure coefficient | | | |
| --- | --- | --- | --- | --- | --- |
| A | B | C | D |
| 5° | Maximum, all values of | +0,6 | +1,8 | +1,3 | +0,4 |
| Minimum, | −0,6 | −1,4 | −1,4 | −1,1 |
| Minimum, | −1,3 | −2,0 | −1,8 | −1,5 |
| 10° | Maximum, all values of | +0,7 | +1,8 | +1,4 | +0,4 |
| Minimum, | −0,7 | −1,5 | −1,4 | −1,4 |
| Minimum, | −1,3 | −2,0 | −1,8 | −1,8 |
| 15° | Maximum, all values of | +0,9 | +1,9 | +1,4 | +0,4 |
| Minimum, | −0,9 | −1,7 | −1,4 | −1,8 |
| Minimum, | −1,3 | −2,2 | −1,6 | −2,1 |
| 20° | Maximum, all values of | +1,1 | +1,9 | +1,5 | +0,4 |
| Minimum, | −1,2 | −1,8 | −1,4 | −2,0 |
| Minimum, | −1,4 | −2,2 | −1,6 | −2,1 |
| 25° | Maximum, all values of | +1,2 | +1,9 | +1,6 | +0,5 |
| Minimum, | −1,4 | −1,9 | −1,4 | −2,0 |
| Minimum, | −1,4 | −2,0 | −1,5 | −2,0 |
| 30° | Maximum, all values of | +1,3 | +1,9 | +1,6 | +0,7 |
| Minimum, | −1,4 | −1,9 | −1,4 | −2,0 |
| Minimum, | −1,4 | −1,8 | −1,4 | −2,0 |

Table D.5 — values for duopitch canopies for *α* < 0°

|  | Blockage | Net pressure coefficient | | | |
| --- | --- | --- | --- | --- | --- |
| A | B | C | A |
| −20° | Maximum, all values of | +0,8 | +1,6 | +0,6 | +1,7 |
| Minimum, | −0,9 | −1,3 | −1,6 | −0,6 |
| Minimum, | −1,5 | −2,4 | −2,4 | −0,6 |
| −15° | Maximum, all values of | +0,6 | +1,5 | +0,7 | +1,4 |
| Minimum, | −0,8 | −1,3 | −1,6 | −0,6 |
| Minimum, | −1,6 | −2,7 | −2,6 | −0,6 |
| −10° | Maximum, all values of | +0,6 | +1,4 | +0,8 | +1,1 |
| Minimum, | −0,8 | −1,3 | −1,5 | −0,6 |
| Minimum, | −1,6 | −2,7 | −2,6 | −0,6 |
| −5° | Maximum, all values of | +0,5 | +1,5 | +0,8 | +0,8 |
| Minimum, | −0,7 | −1,3 | −1,6 | −0,6 |
| Minimum, | −1,5 | −2,4 | −2,4 | −0,6 |

* + 1. Multibay duopitch canopies

(1) For a multibay duopitch canopy, as shown in Figure D.8, each load on a bay may be calculated by applying the reduction factors given in Table D.6 to the values given in Table D.4 and

Table D.5.

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Figure D.8 — Reduction factors for multibay canopies

Table D.6 — Reduction factors for multibay canopies

| Bay | Location | factors for all | |
| --- | --- | --- | --- |
| on maximum (downward) force and pressure coefficients | on minimum (upward) force and pressure coefficients |
| 1 | Outer bay | 1,0 | 0,8 |
| 2 | Second bay | 0,9 | 0,7 |
| 3 | Third and subsequent bays | 0,7 | 0,7 |

* + 1. Porch roofs

(1) The net pressure coefficients in Table D.7 are valid for open flat porch roofs (as shown in Figure D.9), connected to a building wall, with a maximal overhang of 10 m and a roof angle up to ±10° from the horizontal.

(2) The porch roof should be designed for two loading cases, wind force acting upwards (negative) and wind force acting downwards (positive).

(3) The resulting net pressure coefficients , on the upper and lower side should be taken from Table D.6. The notation and dimensions should be taken from Figure D.9.

(4) The values also apply in case of a small gap of up to 10 % of the depth of the porch roof between building wall and the porch roof.

NOTE Reference height is the height as given in Figure D.9. It is defined as the mean value of the eave and ridge height of the building.

Table D.7 — Net pressure coefficients for the resulting pressure on porch roofs

| Height ratio | A | | | B | | |
| --- | --- | --- | --- | --- | --- | --- |
| Down­ward | Upward | | Down­ward | Upward | |
|  |  |  |  |
| ≤ 0,1 | 1,1 | ‑0,9 | ‑1,4 | 0,9 | ‑0,2 | ‑0,5 |
| 0,2 | 0,8 | ‑0,9 | ‑1,4 | 0,5 | ‑0,2 | ‑0,5 |
| 0,3 | 0,7 | ‑0,9 | ‑1,4 | 0,4 | ‑0,2 | ‑0,5 |
| 0,4 | 0,7 | ‑1,0 | ‑1,5 | 0,3 | ‑0,2 | ‑0,5 |
| 0,5 | 0,7 | ‑1,0 | ‑1,5 | 0,3 | ‑0,2 | ‑0,5 |
| 0,6 | 0,7 | ‑1,1 | ‑1,6 | 0,3 | ‑0,4 | ‑0,7 |
| 0,7 | 0,7 | ‑1,2 | ‑1,7 | 0,3 | ‑0,7 | ‑1,0 |
| 0,8 | 0,7 | ‑1,4 | ‑1,9 | 0,3 | ‑1,0 | ‑1,3 |
| 0,9 | 0,7 | ‑1,7 | ‑2,2 | 0,3 | ‑1,3 | ‑1,6 |
| 1,0 | 0,7 | ‑2,0 | ‑2,5 | 0,3 | ‑1,6 | ‑1,9 |
| For intermediate values linear interpolation can be used. Mean values can be linearly interpolated. | | | | | | |

Ein Bild, das Diagramm, technische Zeichnung, Plan, Entwurf enthält.

Automatisch generierte Beschreibung

a) elevation

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Automatisch generierte Beschreibung

b) plan

Key

|  |  |
| --- | --- |
| 1 | porch roof on a gable wall |
| 2 | porch roof on a side wall |
| *e* | = *d*1/4 or *b*1/2, whichever is smaller |

Figure D.9 — Dimensions and division of the areas for porch roofs

* + 1. Balconies

(1) Open balconies and the parapets and/or railings should be designed for horizontal wind forces according to Figure D.10. The forces should be determined using the pressure coefficients according to Table D.8 and the projected outline area as the reference area and should be combined in the most adverse superposition. Vertical loading should be calculated due to D.3.5.

NOTE The net pressure coefficients are given in Table D.8 and the resulting horizontal wind forces and force combinations are shown in Figure D.10 unless the National Annex provides different values.

(2) The net pressure actions and loading zones are sketched in Figure D.10. The loading values are should be taken as specified in Table D.8.

(3) Closed balconies shall be designed according to C.4.2, vertical walls, and respective subsections on roofs.

(4) The reference height to the building itself should be taken as specified in C.4.2.

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Figure D.10 — Combinations of the net pressure coefficients according to Table D.8; Zones A, B, C and D according to Figure C.7

Table D.8 (NDP) — Net pressure coefficients for balconies

| Zone acc. to Fig. C.7 | A | B and C | D |
| --- | --- | --- | --- |
|  | 1,8 | 1,3 | 0,9 |
|  | 2,5 | 2,0 | 1,3 |
| NOTE  Linear interpolation can be applied for intermediate values of . | | | |

* 1. Net pressure coefficients for free-standing walls, parapets, fences and signboards
     1. General

(1) The values of the net pressure coefficients for free-standing walls and parapets depend on the solidity ratio *φ*. For solid walls, the solidity ratio *φ* should be taken as 1, and for walls which are 80 % solid (i.e. have 20 % openings) . Porous walls and fences with a solidity ratio should be treated as single lattice frames in accordance with E.5.10.

NOTE For parapets and noise barriers of bridges, see E.6.

* + 1. Free-standing walls and parapets

(1) For free-standing walls and parapets net pressure coefficients should be specified for the zones A, B, C and D as shown in Figure D.9.

NOTE Values of the resulting pressure coefficients for free-standing walls, parapets and attics can be given in the National Annex. Values are given in Table D.9 for two different solidity ratio, see D.4.1(1). These values correspond to a direction of oblique wind compared to the wall without return corner (see Figure D.6) and, in the case of the wall with return corner, to the two opposite directions indicated in Figure D.9. The reference area in both cases is the gross area. Linear interpolation is used for solidity ratio between 0,8 and 1.

Table D.9 — Net pressure coefficients for free-standing walls and parapets

| Solidity | Zone | | A | B | C | D |
| --- | --- | --- | --- | --- | --- | --- |
|  | Without return corners |  | 2,3 | 1,4 | 1,2 | 1,2 |
|  | 2,9 | 1,8 | 1,4 | 1,2 |
|  | 3,4 | 2,1 | 1,7 | 1,2 |
| with return corners of length a | | ±2,1 | ±1,8 | ±1,4 | ±1,2 |
|  |  | | ±1,2 | ±1,2 | ±1,2 | ±1,2 |
| a Linear interpolation can be used for return corner lengths between 0,0 and . | | | | | | |

(2) The reference height for free standing walls should be taken as , see Figure D.9. The reference height for parapets in buildings should be taken as , see Figure C.8.

(3) For parapets on roof tops, values for inward-facing wind actions should be taken as 1,5 and 2,0 for locations at roof zone G and F, respectively, see zone definition in C.4.3, C.4.4 and C.4.5. For outward-facing wind action, the value should be taken as 1,0.

(4) The net pressure coefficients at attics of low and wide scale hall-like buildings with dimensions between 1:1 and 1:3, and between 0,075 and 0,1 should be taken as = +2,5 in zone A and = +1,7 in zone B (both inward-facing) and = −1,7 (outward-facing) in zone A and zone B (, , and according to Figure C.7).

|  |  |
| --- | --- |
| for *l*>4 *h* | |
| Ein Bild, das Diagramm, Reihe, parallel, technische Zeichnung enthält.  Automatisch generierte Beschreibung | |
| for *l*≤4 *h* | |
| Ein Bild, das Diagramm, Reihe, Text, parallel enthält.  Automatisch generierte Beschreibung | |
| for *l*≤2 *h* | |
| Ein Bild, das Diagramm, Reihe, parallel, Text enthält.  Automatisch generierte Beschreibung | |
| Ein Bild, das Entwurf, Reihe, Zeichnung, Design enthält.  Automatisch generierte Beschreibung | Ein Bild, das Entwurf, Reihe, Diagramm, Zeichnung enthält.  Automatisch generierte Beschreibung |

Key

|  |  |
| --- | --- |
| 1 | without return corner |
| 2 | with return corner |

Figure D.11 — Key to zones of free-standing walls and parapets

* + 1. Shelter factors for walls and fences

(1) If there are other walls or fences windward that are equal in height or taller than the wall or fence of height, , under consideration, then an additional shelter factor may be used with the net pressure coefficients for walls and lattice fences. The value of the shelter factor depends on the spacing between the walls or fences , and the solidity , of the windward (sheltering) wall or fence. Values of are given in Figure D.10 and in Table D.10.

NOTE The shelter factor is given in Table D.10 and shown in Figure D.12 unless the National Annex provides different values.

(2) The resulting net pressure coefficient on the sheltered wall, , should be taken from Formula (D.1):

|  |  |
| --- | --- |
|  | (D.1) |

(3) The shelter factor should not be applied in the end zones within a distance of *h* measured from the free end of the wall (Figure D.13).



Key

|  |  |
| --- | --- |
|  | *φ*= 1,0 |
|  | *φ*= 0,8 |
| *ψ*s | = shelter factor |
| *x/h* | = spacing |

Figure D.12 — Shelter factor for walls and fences for -values between 0,8 and 1,0

Table D.10 — Shelter factor for walls and fences for -values between 0,8 and 1,0

| Spacing |  |  |
| --- | --- | --- |
|  |  | |
|  |  |  |
|  |  |  |
|  |  |  |



Figure D.13 — Area subjected to sheltering

* + 1. Signboards

(1) For signboards separated from the ground by a height greater than (see Figure D.14), the net pressure coefficient should be taken from Formula (D.2):

|  |  |
| --- | --- |
|  | (D.2) |

Formula (D.2) is also applicable where is less than and .

(2) The resultant force normal to the signboard should be taken to act at the height of the centre of the signboard with a horizontal eccentricity .

The value of the horizontal eccentricity should be taken from Formula (D.3):

|  |  |
| --- | --- |
|  | (D.3) |

(3) Signboards separated from the ground by a height less than and with should be treated as boundary walls, see D.4.2.

NOTE 1 Reference height: .

NOTE 2 Reference area: .

(4) Divergence or stall flutter instabilities should be checked.

Ein Bild, das Diagramm, technische Zeichnung, Plan, Reihe enthält.

Automatisch generierte Beschreibung

Figure D.14 — Key for signboards

1. (normative)  
     
   Force coefficients for structures and structural members
   1. Use of this annex

(1) This Normative Annex contains additional provisions to 7.5, specifying force coefficients and friction coefficients.

* 1. Scope and field of application

(1) This Normative Annex covers the choice of force coefficient and the associated reference height, for bluff bodies, circular sections, spheres, lattice structures and scaffolding, flags, iced structures and bridge decks. It also provides friction coefficients for walls, parapets and roof surfaces.

* 1. General
     1. Structures and structural elements with square section

(1) The force coefficient of structures and structural elements of square section should be determined by Formula (E.1):

|  |  |
| --- | --- |
|  | (E.1) |

where

|  |  |
| --- | --- |
|  | is the force coefficient of rectangular sections with sharp corners and without free-end flow; |
|  | is the reduction factor for square sections with rounded corners. depends on Reynolds number; |
|  | is the end-effect factor for elements with free-end flow should be taken as defined in E.3.7. |

(2) For wind blowing normally to a face the force coefficient of square sections with sharp corners and without free-end flow should be taken as .

(3) For major structures, such as large buildings, the values should be verified by testing in appropriate wind turbulence conditions.

NOTE 1 Approximate values of are given in Figure E.1 and were obtained under smooth flow conditions. These coefficients are assumed to be safe.

NOTE 2  Figure E.1 can also be used for buildings with .

(3) For wind blowing in the direction of the diagonal the force coefficient of square sections with sharp corners and without free-end flow should be taken as .

NOTE 1 Approximate values of are given in Figure E.2 and were obtained under smooth flow conditions. These coefficients are assumed to be safe.

NOTE 2 The values of are given in Figure E.2 unless the National Annex gives different values.

Ein Bild, das Diagramm, Reihe, technische Zeichnung, Plan enthält.

Automatisch generierte Beschreibung

Figure E.1 — Reduction factor for a square cross-section with rounded corners – wind blowing normally to a face



Figure E.2 — Reduction factor for a square cross-section with rounded corners – wind blowing in the direction of the diagonal

(4) The reference dimension of the section should be taken as .

(5) The reference height should be taken as equal to the maximum height above ground of the section being considered.

* + 1. Structures and structural elements with rectangular sections

(1) The force coefficient of structural elements of rectangular section with the wind blowing normally to a face should be determined by Formula (E.2):

|  |  |
| --- | --- |
|  | (E.2) |

where

|  |  |
| --- | --- |
|  | is the force coefficient of rectangular sections with sharp corners and without free-end flow as given by Figure E.3; |
|  | is the end-effect factor for elements with free-end flow should be taken as defined in E.3.7. |

(2) The reference dimension of the section should be taken as .

(3) The reference height should be taken as equal to the maximum height above ground of the section being considered.

NOTE For plate-like sections () lift forces at certain wind angles of attack can give rise to higher values of up to an increase of 25 %.



Figure E.3 — Force coefficients of rectangular sections with sharp corners and without free end flow

* + 1. Structural elements with sharp edged section

(1) The force coefficients of structural elements with sharp edged section (e.g. elements with cross- sections such as those shown in Figure E.4) should be determined using Formula (E.3).

|  |  |
| --- | --- |
|  | (E.3) |

where

|  |  |
| --- | --- |
|  | is the end-effect factor (see E.1.7). |

Ein Bild, das Diagramm, Reihe enthält.

Automatisch generierte Beschreibung

Figure E.4 — Sharp edged structural sections

NOTE The value of for all elements without free-end flow is 2,0, unless the National Annex gives a different value. This value is based on measurements under low-turbulent conditions. It is assumed to be a save value.

(2) Formula (E.3) and Figure E.4 may also be used for buildings with h/d > 5,0.

(3) The reference areas (see Figure E.4), should be taken as follows:

|  |  |
| --- | --- |
|  | (E.4) |

where

|  |  |
| --- | --- |
|  | is the length of the structural element being considered. |

(4) In all cases the reference height  should be taken as equal to the maximum height above ground of the section being considered.

* + 1. Structural elements with regular polygonal section

(1) The force coefficient of structural elements with regular polygonal section with 5 or more sides should be determined using Formula (E.5):

|  |  |
| --- | --- |
|  | (E.5) |

where

|  |  |
| --- | --- |
|  | is the end-effect factor should be taken as defined in E.3.7; |
|  | is the force coefficient of structural elements without free-end flow. |

NOTE The values of can be given in the National Annex. Values based on measurements under smooth flow are given in Table E.1.

(2) For buildings where , may be determined from Formula (E.5).

NOTE See also Table E.1 and Figure E.5.

Ein Bild, das Entwurf, Diagramm, Zeichnung, Design enthält.

Automatisch generierte Beschreibung

Figure E.5 — Regular polygonal section

Table E.1 — Force coefficient for regular polygonal sections

| Number of sides | Sections | Finish of surface and of corners | Reynolds number   (a) |  |
| --- | --- | --- | --- | --- |
| 5 | Pentagon | all | All | 1,80 |
| 6 | Hexagon | all | All | 1,60 |
| 8 | Octagon | surface smoothb |  | 1,45 |
|  | 1,30 |
| surface smoothb |  | 1,30 |
|  | 1,10 |
| 10 | Decagon | all | All | 1,30 |
| 12 | Dodecagon | surface smoothc corners rounded |  | 0,90 |
| all others |  | 1,30 |
|  | 1,10 |
| 16–18 | Hexdecagon to octadecagon | surface smoothc corners rounded |  | treat as a circular cylinder, see (C.9) |
|  | 0,70 |
| a Reynolds number with and given in 6.3.1, , is defined in 7.1(2).  b corner radius, diameter of circumscribed circumference, see Figure E.5  c From wind tunnel tests on sectional models with galvanised steel surface and a section with and corner radius of | | | | |

(3) The reference dimension of the section should be taken as .

(4) The reference height should be taken as equal to the maximum height above ground of the section being considered.

* + 1. Structural elements with circular section and stranded cables

(1) The force coefficient for a finite circular cylinder should be determined from Formula (E.6).

|  |  |
| --- | --- |
|  | (E.6) |

where

|  |  |
| --- | --- |
|  | is the force coefficient of cylinders without free-end flow (see Figure E.6); |
|  | is the end-effect factor (see E.3.7). |



Figure E.6 — Force coefficient for circular cylinders without free-end flow and for different equivalent roughness

NOTE 1 Figure E.2 can also be used for building with .

NOTE 2 Figure E.2 is based on the Reynolds number with and given in 6.5.

NOTE 3 The force coefficients are given in Figure E.6, unless the National Annex gives different values.

(2) Values of equivalent surface roughness for new surfaces should be taken from Table E.2.

NOTE For aged surfaces the values of the equivalent surface roughness can be given in the National Annex.

Table E.2 — Equivalent surface roughness

| Type of surface | Equivalent roughness, | Type of surface | Equivalent roughness, |
| --- | --- | --- | --- |
| [mm] | [mm] |
| Glass | 0,0015 | smooth concrete | 0,2 |
| polished metal | 0,002 | planed wood | 0,5 |
| fine paint | 0,006 | rough concrete | 1,0 |
| spray paint | 0,02 | rough sawn wood | 2,0 |
| bright steel | 0,05 | rust | 2,0 |
| cast iron | 0,2 | brickwork | 3,0 |
| galvanised steel | 0,2 |  |  |

(3) The reference dimension of the section is the diameter .

(4) The reference height should be taken as equal to the maximum height above ground of the section being considered.

(5) For cylinders near a plane surface with a distance ratio (see Figure E.7) special advice should be taken into account.

Ein Bild, das Diagramm, Reihe, Entwurf, Kreis enthält.

Automatisch generierte Beschreibung

Figure E.7 — Cylinder near a plane surface

(6) The force coefficient for a finite stranded cable should be determined from Formula (E.7).

|  |  |
| --- | --- |
|  | (E.7) |

where

|  |  |
| --- | --- |
|  | is the force coefficient of cylinders without free-end flow; |
|  | is the end-effect factor (see E.1.7). |

(7) For stranded cables should be taken from Table E.3.

NOTE The force coefficients are given Table E.3 unless the National Annex gives different values.

Table E.3 — Force coefficient for stranded cables

|  |  |  |  |
| --- | --- | --- | --- |
| Member type | Reynolds No | Ice free and glaze ice | Rime ice |
| Fine stranded cable e.g. steel core aluminium conductor, locked-coil strand or spiral steel strand with more than seven wires: |  | 1,2 | 1,6 |
|  | 1,0 | 1,3 |
| Thick stranded cable e.g. small wire ropes, round strand ropes, spiral steel strand with seven strands (1 × 7) | < 2.104 | 1,2 | 1,6 |
| > 4.104 | 1,1 | 1,3 |
| For intermediate values of , the force coefficient should be obtained by linear interpolation.  NOTE 1 The Reynolds number is based upon peak pressure e.g. with and diameter (with ice, if present).  NOTE 2 For long cables, the Reynold number can be found based on the wind speed at the middle of the cable. | | | |

(8) For cylinders with helical strakes of depth up to , shall be taken as 1,20. The reference width shall be taken as the diameter of the cylinder, , plus twice the helical strake depth.

* + 1. Force coefficients for vertical cylinders in a row arrangement

(1) For vertical circular cylinders in a row arrangement, the force coefficient depends on the wind direction related to the row axis and the ratio of distance  and the diameter *b* should be taken as defined in Table E.4. The force coefficient, , for each cylinder may be obtained by Formula (E.8):

|  |  |
| --- | --- |
|  | (E.8) |

where

|  |  |
| --- | --- |
|  | is the force coefficient of cylinders without free-end flow, (see E.3.5); |
|  | is the end-effect factor (see E.3.7); |
|  | is the factor given in Table E.4 (for the most unfavourable wind direction). |

Table E.4 — Factor for vertical cylinders in a row arrangement

|  |  |  |
| --- | --- | --- |
|  |  | Ein Bild, das Diagramm, Kreis, Reihe, technische Zeichnung enthält.  Automatisch generierte Beschreibung |
| 2,5 < *a*/*b* < 3,5 | 1,15 |
| 3,5 < *a*/*b* < 30 |  |
| *a*/*b* > 30 | 1,00 |

NOTE For the values of can be given in the National Annex.

* + 1. Effective slenderness and end-effect factor

(1) Where relevant, the end-effect factor should be determined as a function of slenderness ratio .

NOTE 1 Values, taking the effect of turbulence into account can be specified in the National Annex.

NOTE 2 The force coefficients, , given in E.3.1 to E.3.6 are based on measurements on structures without free-end flow away from the ground. The end-effect factor takes into account the reduced resistance of the structure due to the wind flow around the end (end-effect). Figure E.8 and Table E.5 are based on measurements in smooth flow.

(2) The effective slenderness should be defined depending on the dimensions of the structure and its position.

NOTE 1 Values for are given in Table E.5 and indicative values for are given in Figure E.8 for different solidity ratio .

NOTE 2 End effects depend primarily on the geometric slenderness ratio () and the geometry of the wake leeward of the bluff body (accounted for with the factor ).

Table E.5 — Values of for cylinders, polygonal sections, rectangular sections, sharp edged structural sections and lattice structures

| **Position of the structure, wind normal to the plane of the page** | **Effective slenderness** λ |
| --- | --- |
| Ein Bild, das Diagramm, Reihe, Entwurf, technische Zeichnung enthält.  Automatisch generierte Beschreibung |  |
| for *b*≤ *l* |  |
| Ein Bild, das Diagramm, Text, Reihe, technische Zeichnung enthält.  Automatisch generierte Beschreibung  for *b*≤ *l* |  |
| Ein Bild, das Diagramm, Entwurf, technische Zeichnung, Plan enthält.  Automatisch generierte Beschreibung |  |

Ein Bild, das Reihe, Diagramm, parallel enthält.

Automatisch generierte Beschreibung

Figure E.8 — Indicative values of the end-effect factor as a function of solidity ratio *φ* versus effective slenderness

(3) The solidity ratio (see Figure E.9) is given by Formula (E.9).

|  |  |
| --- | --- |
|  | (E.9) |

where

|  |  |
| --- | --- |
|  | is the sum of the projected areas of the members; |
|  | is the overall envelope area *.* |

Ein Bild, das Reihe, Diagramm, Design enthält.

Automatisch generierte Beschreibung

Figure E.9 — Definition of solidity ratio

* 1. Force coefficients for spheres

(1) The along-wind force coefficient of spheres should be determined as a function of the Reynolds number (see 7.1(2)) and the equivalent roughness (see Table E.2).

NOTE 1 The values of can be given in the National Annex. Values based on measurements in smooth flow are given in Figure E.11. Figure E.11 is based on the Reynolds number with and given in 6.5

NOTE 2 The values in Figure E.11 are limited to values , where is the distance of the sphere from a plain surface, is the diameter (see Figure E.7). For the force coefficient is be multiplied by the factor 1,6.

Ein Bild, das Diagramm, Reihe, Kreis, Entwurf enthält.

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Figure E.10 — Sphere near plain surface

Ein Bild, das Diagramm, Text, Reihe, parallel enthält.

Automatisch generierte Beschreibung

Figure E.11 — Along-wind force coefficient of a sphere

(2) The vertical force coefficient of spheres should be taken from Formula (E.10).

|  |  |
| --- | --- |
|  | (E.10) |

(3) In both cases the reference area should be obtained by Formula (E.11).

|  |  |
| --- | --- |
|  | (E.11) |

(4) The reference height should be taken from Formula (E.12):

|  |  |
| --- | --- |
|  | (E.12) |

* 1. Force coefficients for square and triangular lattice structures and scaffoldings
     1. Scope of this Section

(1) This Clause contains information about force coefficients and the wind resistance of lattice structures and scaffoldings. In addition, it provides information on force coefficients for lattice structures (e.g. towers and guyed masts) when supporting ancillary items.

NOTE The National Annex can give a reduction factor for scaffolding without air tightness devices and affected by solid building obstruction. A recommended value is given in EN 12811-1.

(2) The method given in E.5.4 should be used to determine the force coefficients and wind resistance of bare square or equilateral triangular lattice structures.

(3) The method given in E.5.3 should be used to determine the combined wind resistance of square or equilateral triangular lattice structures supporting ancillary items.

NOTE This clause refers to prEN 1991‑1‑9. The National Annex can give further information.

* + 1. Symbols

(1) In addition to those symbols given in EN 1993‑1‑1, symbols in Clause 3.2 have been used in this Annex.

* + 1. Wind resistance
       1. General

(1) For the purposes of calculating the wind force, the structure should be divided into a series of sections, where a section comprises several identical or nearly identical panels, see Figure E.12. Projections of bracing members in faces parallel to the wind direction, and in plan and hip bracing, should be omitted in the determination of the projected area of the structure.

(2) The structure should generally be divided into a sufficient number of sections to enable the wind loading to be adequately modelled for the global analysis.

(3) The wind force acting on a section or component should be determined according to Annex M.

(4) In determining the wind force under iced conditions, the projected areas of structural elements and ancillaries should be increased to take due account of the thickness of ice as relevant.

* + - 1. Total wind resistance

(1) The total wind resistance in the direction of the wind over a section of the structure should be taken as

|  |  |
| --- | --- |
|  | (E.13) |

where

|  |  |
| --- | --- |
|  | is the wind resistance of the bare lattice section, determined in accordance with E.5.4 using the solidity ratio, , appropriate to the bare structure; |
|  | is the sum of the wind resistances of the ancillaries, determined in accordance with E.5.6 to E.5.8, as appropriate. |

(2) Where the projected areas of ancillaries on each face are within 10 % of each other, then they may be treated as appropriate structural members and the total wind drag calculated in accordance with E.5.4.

|  |  |
| --- | --- |
| Ein Bild, das Diagramm, Reihe, Entwurf, technische Zeichnung enthält.  Automatisch generierte Beschreibung | Ein Bild, das Handwagen, Diagramm, Entwurf enthält.  Automatisch generierte Beschreibung |
| NOTE 1 Face 1 should be taken as windward such  that | NOTE 2 Face 1 should be taken as windward such that . External ladder should be treated as individual item. |
| a) Plan on square structure | b) Plan on triangular structure |
| Ein Bild, das Reihe, parallel, Design enthält.  Automatisch generierte Beschreibung | Ein Bild, das Diagramm, Reihe, Entwurf, technische Zeichnung enthält.  Automatisch generierte Beschreibung |
| c) Mast section | d) Structural panel |

Key

|  |  |
| --- | --- |
| 1 | face 1 |
| 2 | face 2 |
| 3 | face 3 |
| 4 | face 4 |
| 5 | ancillary elements projected normal to face 1 |
| 6 | leg projected normal to face |
| 7 | ancillary elements in this area allocated to face 2 |
| 8 | ancillary elements projected normal to face (inclusive of ladder rungs, hoops etc.) |
| 9 | leg projected normal to face |
| 10 | ancillary elements in this area allocated to face 2 |
| 11 | mast section |
| 12 | ancillary elements having a projected area |
| 13 | structural elements of projected area |
| 14 | panel height () |

Figure E.12 — Projected panel area used to calculate solidity ratio,

* + 1. Wind resistance of the bare lattice

(1) For a lattice structure of square or equilateral triangular plan form, having equal areas on each face, the wind resistance of a section in the direction of the wind:

|  |  |
| --- | --- |
|  | (E.14) |

where

|  |  |
| --- | --- |
|  | is the overall longitudinal force coefficient of a section without end-effects, determined in accordance with E.5.5; |
|  | is the wind incidence factor. |

(2) The wind incidence factor may be obtained from:

|  |  |  |
| --- | --- | --- |
|  | for square structures | (E.15) |
|  | for triangular structures | (E.16) |

with

|  |  |  |
| --- | --- | --- |
|  |  | (E.17) |
|  | for and | (E.18) |
|  | for | (E.19) |
|  | for | (E.20) |

in which

|  |  |
| --- | --- |
|  | is the angle of incidence of the wind to the normal of face 1, in plan — refer to Figure E.11 and Figure E.12; |
|  | is the solidity ratio, defined by Formula (E.21). |

|  |  |
| --- | --- |
|  | (E.21) |

where

|  |  |
| --- | --- |
|  | is the sum of the projected area of the members and gusset plates of the face projected normal to the face; |
|  | is the area enclosed by the boundaries of the face projected normal to the face; |
|  | is the total projected area when viewed normal to the face of the flat-sided section members in the face; |
|  | is the total projected area when viewed normal to the face of the circular-section members in the face in sub critical regimes; |
|  | is the total projected area when viewed normal to the face, of the circular-section members in the face in supercritical regimes; |
|  | is the section height under consideration as shown in Figure E.12; |
|  | is the overall section width, as shown in Figure E.12. |

The reference area shall be taken as .

(3) Projections of bracing members from faces parallel to the wind direction, and plan and hip bracing, should be ignored in determining the projected area of the structure.

(4) Values of for commonly used values of may be obtained from Figure E.12.

(5) Circular-section members, when ice free, should be assumed to be in a sub critical regime when the effective Reynold’s number for the mean wind speed , and may be assumed to be in a supercritical regime when the effective Reynold’s number . For intermediate values of Reynold’s number linear interpolation may be used.

(6) The value of Re should be obtained from 7.1(2).

Ein Bild, das Diagramm, Reihe, Text, parallel enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | square towers, diagonal wind ) |
| 2 | square and triangular towers wind on face |
| 3 | triangular towers, wind parallel to face |
| 4 | triangular towers, wind on corner () |

NOTE For symbols, see 3.2.

Figure E.13 — Wind incidence factor

* + 1. Overall longitudinal force coefficients for the bare lattice

(1) Values of overall longitudinal force coefficients that are applicable to the structural framework of a square or equilateral triangular section composed of both flat-sided and circular-section members when ice free, should be taken as

|  |  |
| --- | --- |
|  | (E.22) |

where , and are the force coefficients for sections composed of flat-sided, sub critical circular and supercritical circular-section members, respectively, given by

|  |  |
| --- | --- |
|  | (E.23) |
|  | (E.24) |
|  | (E.25) |

with

|  |  |
| --- | --- |
| equal to: | 2,25 for square structures. |
|  | 1,9 for triangular structures. |
| equal to: | 1,5 for square structures; |
|  | 1,4 for triangular structures. |

where , , , and should be taken as defined in E.5.4.

(2) For force calculations, circular section members in supercritical regimes may conservatively be assumed to be in sub critical regimes.

(3) Approximate values of these force coefficients may be obtained from Figure E.13. Figure E.13 is based on wind tunnel tests of structures with 0 >

(4) For structures with consideration should be given to the possibility of cross-wind response due to vortex excitation, see Annex H.



a) Square structures

Ein Bild, das Diagramm, Reihe, Text enthält.

Automatisch generierte Beschreibung

b) Triangular structures

Key

|  |  |
| --- | --- |
| 1 | flat-sided, |
| 2 | circular (sub critical), |
| 3 | circular (supercritical), |
| cf,0,j | force coefficient |
| *φ* | solidity ratio |

Figure E.14 — Overall normal force coefficients for square and triangular structures

* + 1. Wind resistance of linear ancillaries

(1) The wind resistance, in the direction of the wind of any linear ancillary part (including waveguides, feeders, etc.) within a panel height should be taken as

|  |  |
| --- | --- |
|  | (E.26) |

where

|  |  |
| --- | --- |
|  | is the overall normal force coefficient appropriate to the item and its effective Reynold’s number, values of which are given in E.3.5 for common isolated individual circular members; a value of shall apply to flat sided sections and plates. |
|  | is a reduction factor to take account of the shielding of the component by the structure itself and may only be taken into account when at least one face of the structure is effectively shielding the component (or vice versa); should be taken from Table E.6 except for circular sections in supercritical flow and for ancillaries not complying with the constraints of E.5.6 (3) in which case ; |
|  | is the angle of wind incidence to the longitudinal axis of any linear member. |

Where is greater than the reduction factor, KA, should be applied to the wind resistance of the bare lattice rather than the wind resistance of the linear ancillaries.

Thus, in such cases, and .

(2) The reference area, , shall be taken as the area of the part visible when viewed in the wind direction including icing when appropriate; for cylinders with strakes, should be based on the overall width, including twice the strake depth.

(3) should be taken as 1,0 for ancillary items that satisfy any of the following conditions:

1. the total projected area of those ancillary parts adjacent to the face under consideration is greater than the projected area of the structural members in that face (see Figure E.12);
2. the total projected area normal to any face on the structure of any single internal or external ancillary is greater than half the gross area of the face of the panel (see Figure E.12);
3. any ancillary that extends more than 10 % beyond the total face width of the structure at that level.

(4) Where relevant, the corresponding torsional force should be calculated using the appropriate coefficient obtained from wind tunnel tests with the relevant moment arm for such torsion.

Table E.6 (NDP)— Reduction factor, , for ancillary items

| Position of ancillaries | Reduction factor, | |
| --- | --- | --- |
| Square or rectangular plan form | Triangular plan form |
| Internal to the section | 0,7 | 0,7 |
| External to the section | 0,7 | 0,7 |

* + 1. Wind resistance of discrete ancillaries

(1) For any discrete ancillary item such as a dish reflector, the wind resistance, in the direction of the wind, should be taken as

|  |  |
| --- | --- |
|  | (E.27) |

where

|  |  |
| --- | --- |
|  | is the force coefficient for the item appropriate to the wind direction and wind speed and should be obtained from wind tunnel tests, generally provided by the manufacturer (with details of the tests and their range of applicability); |
|  | is should be taken as defined in E.3.6. |

(2) The reference area of the item, , shall be taken as defined in the wind tunnel test (or other source data) and shall be compatible with the definition of . It shall include the thickness of ice when appropriate.

(3) The corresponding crosswind force coefficients and lift coefficient should be calculated as for taking the reference direction in plan as normal to the mean wind direction, and as the appropriate coefficient for crosswind and lift.

(4) The corresponding torsional force coefficient should be calculated using the appropriate coefficient, obtained from wind tunnel tests in association with the relevant moment arm for such torsion.

* + 1. Wind resistance of cables and guys

(1) The wind resistance normal to the guys in the plane containing the guy and the wind should be taken as

|  |  |
| --- | --- |
|  | (E.28) |

where

|  |  |
| --- | --- |
|  | is the overall normal force coefficient appropriate to the effective Reynold’s number, the values of which are given in Table E.3 for both ice-free and iced conditions; |
|  | is the angle of wind incidence to the chord. |

(2) The reference area, , shall be taken as

where

|  |  |
| --- | --- |
|  | is the diameter of the guy with or without ice as appropriate; |
|  | is the chord length of the guy (or section of guy under consideration). |

The wind force on guy insulators, where relevant, should be accounted for, either by using their appropriate force coefficients as individual elements along the guy, or by smearing their effect into .

* + 1. Force coefficients for single lattice frames

(1) Values of normal force coefficients for a single lattice frame composed of both flat-sided and circular-section members should be taken as

|  |  |
| --- | --- |
|  | (E.29) |

where , and are the normal force coefficients for flat-sided, subcritical circular- and supercritical circular-section members respectively, given by

|  |  |
| --- | --- |
| for ; and  for | (E.30) |
|  | (E.31) |
|  | (E.32) |

, , , and should be taken as defined in E.3.4.

NOTE This formulation is appropriate for single lattice frames with an aspect ratio of 20 or more (as found in lattice towers and masts). It is safe-sided for lower aspect ratios.

(2) Approximate values of these force coefficients are given in Figure E.15:



Key

|  |  |
| --- | --- |
| 1 | flat-sided, |
| 2 | circular (subcritical), |
| 3 | circular (supercritical), |
| cf,j | force coefficient |
| *φ* | solidity ratio |

NOTE This figure is based on wind tunnel tests of structures with 0 > .

Figure E.15 — Force coefficients for single lattice frames

* 1. Force coefficients for flags

(1) Force coefficients and reference areas for flags are given in Table E.7.

(2) The reference height is equal to the mid-height of the flag above ground.

Table E.7 — Force coefficients for flags

| Flags | |  |  |
| --- | --- | --- | --- |
| **Fixed Flags**  Force normal to the plane | |  | 1,8 |
| a) | **Free Flags** |  |  |
| b) | Force in the plane |  |
| where  is the mass per unit area of the flag;  is the air density (see 6.2 (5));  is the height of the flag  is the in-wind length of the flag | | | |
| NOTE The equation for free flags includes dynamic forces from the flag flutter effect. | | | |

* 1. Force coefficients for iced structures
     1. General

(1) The values of force coefficients, for iced structural members should be determined from E.7.2, and for lattice structures from E.7.3 dependent on the surface condition of the ice.

NOTE The National Annex can give alternative values.

(2) Once ice is accreted, all wind directions should be considered for wind action on iced structure

* + 1. Single members

(1) The force coefficient of an iced structural member should be calculated by taking into account the type of profile, its force coefficient without ice, , the ice class, the type of ice, the width of the member and the wind direction compared to the prevailing icing wind direction.

* + - 1. Force coefficients for glaze

(1) The force coefficients for glaze on bars should be applied for relevant class ICG, see prEN 1991‑1‑9, are given by Formula (E.33):

|  |  |
| --- | --- |
|  | (E.33) |

where

|  |  |
| --- | --- |
|  | is the value of ICG, e.g. ICGX, see prEN 1991‑1‑9; |
|  | is the force coefficient of the bar without ice. |

NOTE If characteristic ice mass is used instead of ice class, can be found by using corresponding to the upper bound of the relevant ice class. E.g. if the characteristic glaze thickness is 25 mm the corresponding ice class is G3 and in Formula (E.33).

(2) This model may be assumed for members up to a width of about 0,3 m (without ice) as for higher dimensions icicles may occur which might increase -values.

NOTE Glaze is considered deposited as a uniform layer of ice on the whole surface of an object. This accretion model tends to smooth out the differences of the member’s cross-section, leading towards a uniform shape. The main effect concerning force coefficients is that -values increase on circular cross-sections and to decrease on edged cross-sections compared to values without ice. This effect increases with higher ice class (IC), see prEN 1991‑1‑9. The final -value is for the highest IC estimated to be about 1,4 as for a circular cross-section with a rough surface. However, icicles can increase the -values.

(3) -values for members with widths between 0,3 m and 5,0 m should be calculated using Formula (E.34) given by:

|  |  |
| --- | --- |
|  | (E.34) |

where

|  |  |
| --- | --- |
|  | is the member width in meter; |
|  | from Formula (E.33) for  m. |

NOTE is the value for  m for appropriate IC, see prEN 1991‑1‑9.

(4) For member width > 5,0 m, -values should be assumed equal to (without ice accretion).

NOTE Large, solid objects are less influenced by ice accretion. Therefore, the effect of glaze can be neglected on members with a width of 5 m and above.

* + - 1. Force coefficients for rime

(1) The values for force coefficient shall be used for rimed structures.

(2) Formula (E.35) and (E.36) should be applied for calculation of which are based on typical natural shapes of ice accretions and for sections of approximately same shape and dimension as the iced members.

NOTE 1 The assumed model for accretion of rime is described in prEN 1991‑1‑9.

NOTE 2 As for glaze, rime accretion also diminishes the difference between force coefficients for profiles with different cross-section shapes.

NOTE 3 For the most severe ICRs, see prEN 1991‑1‑9, all slender members are expected to have the same -values, no matter what the initial profile shape is.

NOTE 4 The -value for the cross-section without ice is . In ICR9, see prEN 1991‑1‑9, the -value is estimated to be 1,6 for all member widths (without ice) up to 300 mm.

(3) The values of for different values of for slender objects up to a member width of 0,3 m should be calculated as:

|  |  |
| --- | --- |
|  | (E.35) |

where

|  |  |
| --- | --- |
|  | is the value of ICR, e.g. ICRX, see prEN 1991‑1‑9. |

NOTE If characteristic ice mass is used instead of ice class, can be found by using corresponding to the upper bound of the relevant ice class. E.g. if the characteristic rime mass is 2 kg/m the corresponding ice class is R4 and in Formula (E.35).

(4) The values of for different values of for slender objects for members wider than 0,3 m should be calculated given as:

|  |  |
| --- | --- |
|  | (E.36) |

where

|  |  |
| --- | --- |
|  | from Formula (E.35) for  m. |

NOTE For wider members the force coefficients are less influenced by ice accretion, and the effect of rime ice can be neglected for member widths above 5,0 m.

* + 1. Lattice structures
       1. General

(1) The calculation model for wind load on an iced lattice structure — like a lattice tower or mast — should be the same as for the determination of wind loads assuming that no ice is present.

(2) For the determination of wind loads on an iced lattice structure the structural dimensions should be increased with the thickness of ice when calculating the projected area and the solidity ratio, and force coefficients should be modified to account for the iced elements.

(3) The thickness of the ice should be based on the adjusted amount of ice for the relevant combination of wind and ice, see EN 1990.

* + - 1. Overall longitudinal force coefficients for the iced lattice structure

(1) It is assumed that the ice is added on each individual member with a constant thickness on the member calculated from the relevant ice mass per unit length and density rime.

(2) The estimate of the force coefficient for a lattice section and for a given Ice Class can then be done in the following way:

|  |  |
| --- | --- |
|  | (E.37) |

where

|  |  |
| --- | --- |
|  | is the force coefficient for the maximum ice of the icing type (ICR9 or ICG5, see prEN 1991‑1‑9); |
|  | is the number of the Ice Class for the specific ice type; |
|  | is the number of the highest Ice Class ( for ICR and for ICG, see prEN 1991‑1‑9); |
| , , , should be taken as defined in E.5.4. | |

(3) Values of overall normal force coefficients that are applicable to the structural framework of a square or equilateral triangular section composed of both flat-sided and circular-section members, iced according to the highest Ice Class should be taken as:

|  |  |
| --- | --- |
| for rime | (E.38) |

where

|  |  |
| --- | --- |
|  | is the force coefficient for un-iced sections composed of flat-sided elements; |
|  | is the force coefficients for un-iced sections composed of sub-critical circular members given in Formula (E.24). The values without ice should be based on the solidity ratio corresponding to the section with ice included on the members. |

|  |  |
| --- | --- |
| for glaze | (E.39) |

(4) Approximate values for and may be obtained from Figure E.16.

If the cross section is fully blocked, the force coefficient should be based on Formula (E.36).



a) Square structures

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Automatisch generierte Beschreibung

b) Triangular structures

Key

|  |  |
| --- | --- |
| 1 | flat sided, no ice |
| 2 | full rime ice, ICR9 |
| 3 | full glaze ice, ICG5 |
| 4 | circular sub-critical, no ice |
| 5 | circular super-critical, no ice |
| *c*S,I | overall normal force coefficient |
| *φ* | solidity ratio |

Figure E.16 — Overall normal force coefficients for iced square and triangular lattice structures (with non-iced force coefficients also shown)

* + 1. Wind resistance under iced conditions

(1) In determining the wind resistance of a structure and ancillaries under iced conditions, each element of the structure, ancillary parts and guys should be taken as coated on all sides by ice, with a thickness equal to that given in prEN 1991‑1‑9.

(2) Where the gap between components when not iced, is less than 75 mm, this should be assumed to be completely filled by ice under icing conditions.

(3) Force coefficients of individual members should be obtained from Table E.3.

(4) Consideration should be given to asymmetric ice in which some guys are iced, and some are ice-free (see Annex C).

* 1. Force coefficients for bridge decks
     1. General

(1) This Clause only applies to bridges of constant depth and with cross-sections as shown in Figure E.17 consisting of a single deck with one or more spans.

NOTE 1 Wind actions for other types of bridges (e.g. arch bridges, bridges with suspension cables or cable stayed, roofed bridges, moving bridges and bridges with multiple or significantly curved decks) can be defined in the National Annex.

NOTE 2 The angle of the wind direction to the deck axis in the vertical and horizontal planes can be defined in the National Annex.

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Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | truss or plate |
| 2 | open or closed |

Figure E.17 — Cross-sections of normal construction decks

(2) Wind forces exerted on decks are dealt with in E.8.1 and E.8.2. The forces exerted on various parts of a bridge due to wind blowing in the same direction should be considered as simultaneous if they are unfavourable.

(3) Wind actions on bridges produce forces in the , and -directions as shown in Figure E.17,

where

|  |  |
| --- | --- |
| -direction | is the direction parallel to the deck width, perpendicular to the span |
| -direction | is the direction along the span |
| -direction | is the direction perpendicular to the deck |

The forces produced in the *x*- and *y*-directions are due to wind blowing in different directions and normally are not simultaneous. The forces produced in the *z*-direction can result from the wind blowing in a wide range of directions; if they are unfavourable and significant, they should be taken into account as simultaneous with the forces produced in any other direction.

NOTE The notation used for bridges has historically differed from that defined in 3.2. For consistency throughout this Standard, the following notations will now be used for bridges:

|  |  |
| --- | --- |
|  | dimension in the span wise direction (-direction in Figure E.18); |
|  | dimension in the along-wind direction (-direction in Figure E.18); |
|  | dimension in the across-wind (-direction in Figure E.18). |

Ein Bild, das Entwurf, Diagramm, Reihe, Zeichnung enthält.

Automatisch generierte Beschreibung

Figure E.18 — Dimensions of a bridge section subjected to wind actions

(4) Where road traffic is considered to be simultaneous with the wind (see A2.2.1 and A2.2.2 in Annex A2 to EN 1990:2023) the combination value of the wind action on the bridge and on the vehicles should be limited to a value determined by substituting a value for the fundamental value of the basic velocity *.*

NOTE The value for is 23 m/s unless the National Annex gives a different value.

(5) Where railway traffic is considered to be simultaneous with the wind (see A2.2.1 and A2.2.4 in Annex A2 to EN 1990:2023) the combination value of the wind action on the bridge and on the trains should be limited to a value determined by substituting a value for the fundamental value of the basic velocity *.*

NOTE The value of is 25 m/s unless the National Annex gives a different value.

* + 1. Force coefficients
       1. General

(1) Force coefficients for parapets and gantries on bridges should be determined were relevant.

NOTE The National Annex can give force coefficients for parapets and gantries on bridges.

* + - 1. Force coefficients in ‑direction (general method)

(1) Force coefficients for wind actions on bridge decks in the -direction are given by Formula (E.40):

|  |  |
| --- | --- |
|  | (E.40) |

where

|  |  |
| --- | --- |
|  | is the force coefficient without free-end flow. |

NOTE 1 A bridge has usually no free-end flow because the flow is deviated only along two sides (over and under the bridge deck).

NOTE 2 can be taken from Figure E.19.

|  |
| --- |
| Ein Bild, das Diagramm, Plan, technische Zeichnung enthält.  Automatisch generierte Beschreibung |
| *A*ref,x = *b*tot ⋅ *L* |
| Ein Bild, das Text, Diagramm, Reihe, Schrift enthält.  Automatisch generierte Beschreibung |

Key

|  |  |
| --- | --- |
| 1 | bridge type |
| 2 | trusses separated |
| a) | construction phase, open parapets (more than 50 % open) and open safety barriers |
| b) | solid parapets, noise barrier, solid safety barriers or traffic |

Figure E.19 — Force coefficient for bridges,

(2) Where the angle of inclination of the wind exceeds 10°, the drag coefficient should be derived from special studies. This angle of inclination may be due to the slope of the terrain in the on-coming wind direction.

(3) Where two generally similar decks are at the same level and separated by a gap not significantly exceeding 1 m, the wind force on both structures may be calculated as if it were a single structure. In other cases, special consideration may have to be given to wind-structure interaction.

NOTE Where two decks are adjacent, they modify the airflow and the resulting distribution of loading between the two decks. In the case of normal bridges on separate foundations then each bridge can be designed as if the other was not present. In the case of shared foundations, wind tunnel testing can be of value to correctly determine the distribution of loads between the decks and to the foundation. The assumption of simultaneous loading on both decks is generally conservative, noting that, for some structures, wind loading on one deck at a time can be more critical.

(4) Where the windward face is inclined to the vertical (see Figure E.20), the drag coefficient may be reduced by 0,5 % per degree of inclination, from the vertical, limited to a maximum reduction of 30 %.

Ein Bild, das Diagramm, Reihe, Design enthält.

Automatisch generierte Beschreibung

Figure E.20 — Bridge with inclined windward face

NOTE This reduction is not applicable to , defined in E.8.2.3, unless otherwise specified in the National Annex.

(5) Where a bridge deck is sloped transversely, should be increased by 3 % per degree of inclination, but not more than 25 %.

(6) Reference areas for load combinations without traffic load should be based on the relevant value of *b*tot should be taken as defined in Figure E.21 and Table E.8:

1. for decks with plain (web) beams, the sum of:
2. the face area of the front main girder,
3. the face area of those parts of the other main girders projecting under (under looking) this first one,
4. the face area of the part of one cornice or footway or ballasted track projecting over the front main girder,
5. the face area of solid restraints or noise barriers, where relevant, over the area described in 3) or, in the absence of such equipment, 0,3 m for each open parapet or barrier.
6. for decks with trussed girders, the sum of:
7. the face area of one cornice or footway or ballasted track,
8. those solid parts of all main truss girders in normal projected elevation situated above or underneath the area as described in 1),
9. the face area of solid restraints or noise barriers, if relevant, over the area described in 1) or, in the absence of such equipment, 0,3 m for each open parapet or barrier,
10. However, the total reference area should not exceed that obtained from considering an equivalent plain (web) beam of the same overall depth, including all projecting parts.
11. for decks with several main girders during construction, prior to the placement of the carriageway slab: the face area of two main girders.

Ein Bild, das Entwurf, Diagramm, Zeichnung, technische Zeichnung enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | open parapet |
| 2 | open safety barrier |
| 3 | solid parapet, noise barrier or solid safety barrier  dimensions in millimetres |

Figure E.21 — Dimension to be used for

Table E.8 — Dimension to be used for

| Road restraint system | on one side | on both sides |
| --- | --- | --- |
| Open parapet or open safety barrier |  |  |
| Solid parapet or solid safety barrier |  |  |
| Open parapet and open safety barrier |  |  |

(7) Reference areas for load combinations with traffic load are as specified in (4), with the following modification. Instead of the areas described above in a) 3) and 4) and b) 3), the following should be taken into account where they are larger:

1. for road bridges, a height of 2 m from the level of the carriageway, on the most unfavourable length, independently of the location of the vertical traffic loads,
2. for railway bridges, a height of 4 m from the top of the rails, on the total length of the bridge.

(8) The reference height, , may be taken as the distance from the lowest ground level to the centre of the bridge deck structure, disregarding other parts (e.g. parapets) of the reference areas.

* + - 1. Force in -direction — Simplified Method

(1) Where it has been assessed that a dynamic response procedure is not necessary, the wind force in the *x*-direction may be obtained, as an alternative to the general method of Chapter 7, using Formula (E.41):

|  |  |
| --- | --- |
|  | (E.41) |

where

|  |  |
| --- | --- |
|  | is the basic wind speed (see 6.2 (2)); |
|  | is the wind load factor. , where is the exposure factor given in 6.5 and should be taken from E.8.2.2(1); |
|  | is the reference area given in E.8.2.2; |
|  | is the density of air (see 6.5). |

NOTE -values can be defined in the National Annex. Recommended values are given in Table E.9.

Table E.9 — Recommended values of the force factor for bridges

|  |  |  |
| --- | --- | --- |
|  | 6,7 | 8,3 |
|  | 3,6 | 4,5 |
| This table is based on the following assumptions:  – terrain category II according to Table 6.1  – force coefficient  may be taken from Figure E.19  –  –  For intermediate values of , and of linear interpolation may be used. | | |

* + - 1. Wind forces on bridge decks in ‑direction

(1) Force coefficients should be defined for wind action on the bridge decks in the *z*‑direction, both upwards and downwards (lift force coefficients).

(2) In the absence of wind tunnel tests the recommended value may be taken equal to ± 0,9. This value takes globally into account the influence of a possible transverse slope of the deck, of the slope of terrain and of fluctuations of the angle of the wind direction with the deck due to turbulence.

(3) As an alternative may be taken from Figure E.22.

In using it:

* The depth may be limited to the depth of the deck structure, disregarding the traffic and any bridge equipment; and
* For flat, horizontal terrain the angle α of the wind with the horizontal may be taken as ± 5° due to turbulence. This is also valid for hilly terrain when the bridge deck is at least 30 m above ground.

NOTE 1 This wind forces on bridge decks in 𝒛-direction force can have significant effects only if the force is of the same order as the dead load.

NOTE 2 The National Annex can give values for

|  |
| --- |
| Ein Bild, das Diagramm, Entwurf, Reihe, Zeichnung enthält.  Automatisch generierte Beschreibung |
| *A*ref,z = *d*⋅ *L* |
| Ein Bild, das Diagramm, Reihe, Text enthält.  Automatisch generierte Beschreibung |

Key

|  |  |
| --- | --- |
| *α* | Angle of the wind with the horizontal |
| *β* | Superelevation |
| *θ* | = *α* + *β* |

Figure E.22 — Force coefficient for bridges with transversal slope and wind inclination

(2) The reference area is equal to the plan area (see Figure E.17):

|  |  |
| --- | --- |
|  | (E.42) |

(3) No end-effect factor should be taken into account.

(4) The reference height is the same as for (see E.8.2.2(8)).

(5) If not otherwise specified the eccentricity of the force in the *x*‑direction may be set to , see Figure E.22.

* + - 1. Wind forces on bridge decks in y‑direction

(1) If necessary, the longitudinal wind forces in *y*‑direction should be taken into account.

NOTE The National Annex can give the values. The recommended values are:

* for plated bridges, 25 % of the wind forces in ‑direction,
* for truss bridges, 50 % of the wind forces in ‑direction.
  1. Friction coefficients

(1) Friction should be considered for the cases should be taken as defined in 7.5 (3).

(2) The friction coefficients , for walls and roof surfaces given in Table E.10, should be used.

(3) The reference area should be taken from Figure E.23. For buildings, friction forces should be applied on the part of the external surfaces parallel to the wind, located beyond a distance from the windward eaves or corners, equal to the smallest value of or .

(4) The reference height should be taken equal to the structure height above ground or building height , see Figure E.23.

Table E.10 — Frictional coefficients for walls, parapets and roof surfaces

| Surface | Friction coefficient |
| --- | --- |
| Smooth (i.e. steel, smooth concrete) | 0,01 |
| Rough (i.e. rough concrete, tar-boards) | 0,02 |
| Very rough (i.e. ripples, ribs, folds) | 0,04 |



Figure E.23 — Reference area for friction

1. (informative)  
     
   Procedure for along-wind dynamic response
   1. Use of this annex

(1) This Informative Annex provides complementary/supplementary guidance to 8 for determining the structural factor.

NOTE National choice on the application of this Informative Annex is given in the National Annex. If the National Annex contains no information on the application of this informative annex, it can be used.

* 1. Scope and field of application

(1) This Informative Annex applies to buildings, bridges, towers, masts, chimneys and other engineering structures.

(2) This Informative Annex does not apply to structures with large variation of across-wind dimension.

* 1. Along-wind dynamic response

(1) The procedure for along-wind dynamic response covers structures where only one dominant mode is significant for the vibrations of the structure.

NOTE The response contribution from non-dominant modes for along-wind vibration can be assumed negligible.

(2) General shapes of structures covered by the detailed procedure are shown in Figure F.2 for structures with constant sign mode shapes and in Figure F.14 for structures with non-constant sign mode shapes.

NOTE 1 The detailed procedure can also apply to other structures with non-rectangular plans.

NOTE 2 For structures with constant sign mode shapes, the static influence lines are assumed to be of similar shape, see F.3. For structures with non-constant sign mode shapes, the static influence lines are illustrated in Table F.3.

(3) For structures with constant sign mode shapes F.5 specifies the calculation of the structural factor . The associated displacements and accelerations are specified in F.5.4.

(4) F.7 specifies the equivalent static wind force for structures with non-constant sign mode shapes. The associated displacements and accelerations are specified in F.5.4.

(5) When resonance response is dominating, the mass per unit length is assumed constant where movement is significant.

* 1. Along-wind turbulence

(1) The wind distribution over frequencies should be expressed by the one-sided non-dimensional power spectral density function as determined using Formula (F.1):

|  |  |
| --- | --- |
|  | (F.1) |

where the non-dimensional frequency is determined using Formula (F.2):

|  |  |
| --- | --- |
|  | (F.2) |

where

|  |  |
| --- | --- |
|  | is the fundamental natural frequency of the structure in Hz; |
|  | is the characteristic mean wind velocity, see 6.3.1(1), Formula (6.4); |
|  | is the turbulence length scale should be taken as defined in Formula (F.3). |

The power spectral density function is illustrated in Figure F.1.

Ein Bild, das Diagramm, Reihe enthält.

Automatisch generierte Beschreibung

Figure F.1 — Power spectral density function

NOTE The horizontal across-wind and the vertical power spectra density functions are given in H.4.2.2 (2).

(2) For heights below 300 m the turbulent length scale, which represents the average gust size for natural winds, may be calculated using Formula (F.3):

|  |  |
| --- | --- |
|  | (F.3) |

with a reference height of , a reference length scale of , and with , where the roughness length is in meters.

(3) The minimum height should be taken from Table 6.1.

* 1. Constant sign mode shapes
     1. General

(1) The procedure for calculating the structural factor for the along-wind dynamic response for constant sign mode shapes should be taken from Table F.1.

Table F.1 — Calculation procedure for determination of the along-wind dynamic response

| Parameter | Subject reference |
| --- | --- |
| Structures covered by the procedure | F.5.1  Figure F.2 |
| Background response factor | F.6 (F.10) |
| Resonance response factor | F.7 (F.15) |
| Structural factor | F.5.3 (F.4) |

(2) The values of for various types of structures should be taken from the Figures in F.3.2.

* + 1. Structures covered by the procedure

|  |  |
| --- | --- |
| **a. Parallel oscillator or point-like structures such as signboards.** | |
| Ein Bild, das Entwurf, Diagramm, Zeichnung, technische Zeichnung enthält.  Automatisch generierte Beschreibung | Ein Bild, das Entwurf, Zeichnung, Diagramm, Reihe enthält.  Automatisch generierte Beschreibung |
|  | Equivalent static wind force |
| **b. Vertical structures such as buildings.** | |
| Ein Bild, das Entwurf, Zeichnung, Diagramm, Design enthält.  Automatisch generierte Beschreibung | Ein Bild, das Entwurf, Zeichnung, Darstellung, Schwarzweiß enthält.  Automatisch generierte Beschreibung |
|  | Equivalent static wind force |
| **c. Horizontal structures such as bridges simply supported.** | |
| Ein Bild, das Entwurf, Zeichnung, Diagramm, Design enthält.  Automatisch generierte Beschreibung | Ein Bild, das Entwurf, Zeichnung, Reihe, Diagramm enthält.  Automatisch generierte Beschreibung |
|  | Equivalent static wind force |
| **d. Horizontal structures such as bridges clamped at the supports.** | |
| Ein Bild, das Entwurf, Zeichnung, Diagramm, technische Zeichnung enthält.  Automatisch generierte Beschreibung | Ein Bild, das Entwurf, Diagramm, Reihe, Zeichnung enthält.  Automatisch generierte Beschreibung |
|  | Equivalent static wind force |

Key

|  |  |
| --- | --- |
| 1 | *F*w,p |

Figure F.2 — Structural dimensions and reference heights for structures where

* + 1. values for buildings and chimneys

(1) Figure F.3 to Figure F.7 illustrates the structural factor for selected structures and wind conditions. The natural frequencies of the structures are estimated using the Formulas given in Annex I.

NOTE For 1,1 the detailed procedure can be applied (approved minimum value of ).

|  |  |  |
| --- | --- | --- |
| **Multi-storey steel buildings:** | | Ein Bild, das Reihe, Text, Diagramm, Screenshot enthält.  Automatisch generierte Beschreibung |
| Roughness length  – solid lines |  |
| Roughness length  (dashed lines) |  |
| Basic wind velocity |  |
| Logarithmic decrement of aerodynamic damping |  |
| Logarithmic decrement of structural damping |  |
| The natural frequencies are derived from Formula (I.2).  Dimensions of *h* and *b* are in metres | |

Figure F.3 — for multi-storey steel buildings with rectangular ground plan and vertical external walls, with regular distribution of stiffness and mass

|  |  |  |
| --- | --- | --- |
| **Multi-storey concrete buildings:** | | Ein Bild, das Reihe, Diagramm, Text enthält.  Automatisch generierte Beschreibung |
| Roughness length  – solid lines |  |
| Roughness length  (dashed lines) |  |
| Basic wind velocity |  |
| Logarithmic decrement of aerodynamic damping |  |
| Logarithmic decrement of structural damping |  |
| The natural frequencies are derived from Formula (I.1).  Dimensions of *h* and *b* are in metres | |

Figure F.4 — for multi-storey concrete buildings with rectangular ground plan and vertical external walls, with regular distribution of stiffness and mass

|  |  |  |
| --- | --- | --- |
| **Steel chimneys without liners:** | | Ein Bild, das Reihe, Diagramm, Text, parallel enthält.  Automatisch generierte Beschreibung |
| Roughness length  – solid lines |  |
| Roughness length  (dashed lines) |  |
| Basic wind velocity |  |
| Logarithmic decrement of aerodynamic damping |  |
| Logarithmic decrement of structural damping |  |
|  |  |
|  |  |
| The natural frequencies are estimated using the Formulas given in Annex I.  Dimensions of *h* and *b* are in metres | |

Figure F.5 — for steel chimneys without liners

|  |  |  |
| --- | --- | --- |
| **Concrete chimneys without liners:** | | Ein Bild, das Text, Reihe, Diagramm, parallel enthält.  Automatisch generierte Beschreibung |
| Roughness length  – solid lines |  |
| Roughness length  (dashed lines) |  |
| Basic wind velocity |  |
| Logarithmic decrement of aerodynamic damping |  |
| Logarithmic decrement of structural damping |  |
|  |  |
|  |  |
| The natural frequencies are estimated using the Formulas given in Annex I.  Dimensions of *h* and *b* are in metres | |

Figure F.6 — for concrete chimneys without liners

|  |  |  |  |
| --- | --- | --- | --- |
| **Steel chimneys with liners:** | | | Ein Bild, das Text, Reihe, Diagramm, parallel enthält.  Automatisch generierte Beschreibung |
| Roughness length  – solid lines | |  |
| Roughness length  (dashed lines) | |  |
| Basic wind velocity | |  |
| Logarithmic decrement of aerodynamic damping | |  |
|  | |  |
|  | |  |
| Logarithmic decrement of structural damping according to table I.2: | | |
|  |  | |
|  |  | |
|  |  | |
| The natural frequencies are estimated using the Formulas given in Annex I.  Dimensions of *h* and *b* are in metres | | |

Figure F.7 — for steel chimneys with liners and different values of

* + 1. Calculation of the structural factor

(1) The equivalent static wind force , see Figure F.2, acting on a structure should be taken as defined in Formula (7.4) and (7.5) and includes the structural factor . The procedure for calculating the structural factor should be taken from Formula (F.4):

|  |  |
| --- | --- |
|  | (F.4) |

where

|  |  |
| --- | --- |
|  | is the reference height for determining the structural factor, see Figure F.2; |
|  | is the linearized peak factor for background response defined as the ratio of the expected maximum value over 10 minutes of the fluctuating background response to its standard deviation. |
|  | is the peak factor for resonance response defined as the ratio of the expected maximum value over 10 minutes of the fluctuating resonant response to its standard deviation, see Formula (F.19) in F.8; |
|  | is the along-wind turbulence intensity defined in 6.4 or B.8 for the reference height given in Figure F.2; |
|  | is the background response factor, modelling the lack of full correlation of the pressures on the structure surface, see F.6; |
|  | is the resonance response factor, modelling turbulence in resonance with the vibrations of the structure, see F.7; |

(2) is equal to , where the size factor takes into account the reduction effect on the wind action due to the non-simultaneity of occurrence of the peak wind pressures on the surfaces and can be obtained from Formula (F.5):

|  |  |
| --- | --- |
|  | (F.5) |

and the dynamic factor taking into account the size effect and the increasing effect from vibrations due to turbulence in resonance with the structure and should be taken as defined in Formula (F.6):

|  |  |
| --- | --- |
|  | (F.6) |

NOTE 1 is calculated using a linearized peak velocity pressure , disregarding the term . The peak velocity pressure is defined in Formula (6.10) and (6.11) in 6.5 (1).

NOTE 2 The value of is 3,5 unless the National Annex gives a different value.

* + 1. Displacements and accelerations

(1) The maximum along-wind displacement is the static displacement determined from the equivalent static wind force defined Formula (7.4) and Formula (7.5).

(2) The characteristic along-wind peak acceleration of the structural point with coordinate along the structural main axis is approximately given by Formula (F.7):

|  |  |
| --- | --- |
|  | (F.7) |

where

|  |  |
| --- | --- |
|  | is the force coefficient and should be taken as defined in 7.5 or Annex E; |
|  | is the characteristic mean velocity pressure, see 6.3.1; |
|  | is the width of the structure and should be taken as defined in Figure F.2; |
|  | is the load distribution factor for resonant turbulence (3). |
|  | is the reference mass per unit length, see I.4; |
|  | is the mode shape, see Annex I; |
|  | is the mode shape value at the point with maximum amplitude; |
| and , and follow the definitions in F.5.3. | |

NOTE The force coefficient can be taken as where relevant.

(3) For mode shapes given by where as in Formula (I.8), the load distribution factor for resonant turbulence is given by Formula (F.8):

|  |  |
| --- | --- |
|  | (F.8) |

NOTE 1 Annex I describes structures for mode shapes with = 0,6, 1,0, 1,5, 2,0 and 2,5, see Figure I.3.

NOTE 2 For case a, c and d in Figure F.2, can be taken as 1,00, 1,23 and 1,53, respectively.

* + 1. Admittance functions

(1) The admittance function describes the conversion of wind velocity power spectra to wind load power spectra. It is specified by the cross-sectional admittance function multiplied with a span-wise admittance function based on the correlation of the incoming undisturbed air flow along the main axis of the structure, see Figure F.8. The admittance function depends on the static influence line for background response and on the mode shape for resonant response.

| Vertical structure | Horizontal structure |
| --- | --- |
| Ein Bild, das Entwurf, Diagramm, Zeichnung, technische Zeichnung enthält.  Automatisch generierte Beschreibung | Ein Bild, das Entwurf, Zeichnung, Diagramm, technische Zeichnung enthält.  Automatisch generierte Beschreibung |

Key

|  |  |
| --- | --- |
| 1 | Cross-sectional admittance |
| 2 | Correlation of wind |

Figure F.8 — Cross-sectional admittance and correlation of wind where

(2) The admittance functions for constant sign static influence lines and mode shapes are described via a basic reference case given by Formula (F.9) and shown in Figure F.9:

|  |  |  |
| --- | --- | --- |
| Constant sign: |  | (F.9) |

where

|  |  |
| --- | --- |
|  | is a non-dimensional size parameter defined as the ratio between a structural dimension and a characteristic air flow dimension. For background turbulence based on static influence lines, the air flow dimension is an integral length scale describing the flow correlations. For resonance turbulence based on mode shapes, the air flow dimension is a length scale corresponding to the natural frequency of the structure considered. |

For the background response factor, the cross sectional and span-wise admittance functions are given using and , respectively, see Formula (F.10).

For the resonance response factor, the cross sectional and span-wise admittance functions are given using  and , respectively, see Formula (F.15).

Ein Bild, das Reihe, Diagramm, parallel, Muster enthält.

Automatisch generierte Beschreibung

Figure F.9 — Admittance function for uniform static influence lines and mode shapes

* 1. Background response factor

(1) The background response factor , which models the lack of correlation of the pressures on the structure surfaces and should be taken from Formula (F.10) using the non-dimensional background size parameters given in Formula (F.11) and (F.12):

|  |  |
| --- | --- |
|  | (F.10) |
|  | (F.11) |
|  | (F.12) |

where

|  |  |
| --- | --- |
|  | is the cross-sectional admittance function taking into account the lack of correlation of pressures acting in a cross section and it is calculated by Formula (F.9); |
|  | is the span-wise admittance function taking into account the lack of correlation of forces acting along the length of the structure and it is calculated by Formula (F.9); |
|  | is the non-dimensional cross-sectional background size parameter; |
|  | is the non-dimensional span-wise background size parameter; |
|  | is the turbulent length scale given in Formula (F.3). |
| and should be taken as defined in Figure F.8. It is on the safe side to use . | |

NOTE 1 is an upper value of the cross-sectional background admittance function and it is determined by correlations of the incoming, undisturbed air flow using the non-dimensional background size parameter for the cross section. The background admittance function can include lack of correlation of pressures on the front side and leeward side, respectively. It is safe to use .

If the correlation factor given in C.4.2 (7) is used, the cross-sectional background admittance function should be set to 1.

NOTE 2 is an approximation of the span-wise background admittance function and it is determined by correlations of the incoming, undisturbed air flow using the non-dimensional background size parameter for the structural length.

(2) The background response factor is illustrated in Figure F.10.

Ein Bild, das Reihe, Diagramm, parallel enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | *b* = 0 |
| 2 | *b* = 0,25 ⋅ *l* |
| 3 | *b* = *l* |

Figure F.10 — Background response factor

(3) For vertical structures with constant sign mode shape cases with a single support, the cross-sectional and span-wise background admittance functions for responses at level above the foundation may be determined for the non-dimensional size parameters should be taken as specified in Formula (F.13) and (F.14):

|  |  |
| --- | --- |
|  | (F.13) |

and

|  |  |
| --- | --- |
|  | (F.14) |

where .

NOTE Relevant for structures such as tall buildings, towers and masts.

* 1. Resonance response factor

(1) The resonance response factor , which models turbulence in resonance with the considered vibration mode of the structure and should be taken from Formula (F.15) using the non-dimensional resonance size parameters should be taken from Formula (F.16) and (F.17):

|  |  |
| --- | --- |
|  | (F.15) |
|  | (F.16) |
|  | (F.17) |

where

|  |  |
| --- | --- |
|  | is the total logarithmic decrement of damping given in I.5; |
|  | is the non-dimensional power spectral density function given in F.2 (1); |
|  | is the cross-sectional resonance admittance function taking into account the lack of correlation of pressures acting in a cross section at the natural frequency and it is calculated by Formula (F.9); |
|  | is the span-wise resonance admittance function taking into account the lack of correlation of forces acting along the length of the structure at the natural frequency and it is calculated by Formula (F.9); |
|  | is the non-dimensional cross-sectional resonance size parameter; |
|  | is the non-dimensional span-wise resonance size parameter. |
| and should be taken as defined in Figure F.8. The characteristic mean wind velocity should be taken from 6.3.1(1), Formula (6.4) and the frequency. | |

NOTE 1 is an upper value of the cross-sectional admittance function and it is determined by correlations of the incoming, undisturbed air flow using the non-dimensional cross-sectional resonance size parameter.

If the correlation factor given in the C.4.2 (10) is used, the cross-sectional resonance admittance function should be set to 1.

NOTE 2 is an approximation of the span-wise admittance function and it is determined by correlations of the incoming, undisturbed air flow using the non-dimensional span-wise resonance size parameter.

(2) The admittance function for resonance response is illustrated in Figure F.11.

Ein Bild, das Diagramm, Reihe, Text, parallel enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | *b* = 0 |
| 2 | *b* = 0,25 ⋅ *l* |
| 3 | *b* = *l* |

Figure F.11 — Admittance function

(3) For vertical structures with constant sign mode shape cases with a single support, the resonance factor for responses at level above the foundation may be determined by Formula (F.18):

|  |  |  |  |
| --- | --- | --- | --- |
|  | for |  | (F.18) |
|  | for |  |  |

where should be taken from Formula (F.15) for .

Formula (F.18) is illustrated in Figure F.12.

Ein Bild, das Reihe, Diagramm, parallel, Text enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | 𝜁 = 0,6 |
| 2 | 𝜁 = 1,0 |
| 3 | 𝜁 = 1,5 |
| 4 | 𝜁 = 2,0 |
| 5 | 𝜁 = 2,5 |

Figure F.12 — Resonance response factor for

NOTE 1 The acceleration in Formula (F.7) is not influenced by Formula (F.18).

NOTE 2 Relevant for structures such as tall buildings, towers and masts.

* 1. Peak factor for resonant response

(1) The peak factor for resonant response, defined as the ratio of the expected maximum value over 10 minutes of the fluctuating resonant response to its standard deviation, should be obtained from Formula (F.19) and is shown in Figure F.13.

Ein Bild, das Diagramm, Reihe, parallel enthält.

Automatisch generierte Beschreibung

Figure F.13 — Peak factor for resonant response

|  |  |
| --- | --- |
|  | (F.19) |

where

|  |  |
| --- | --- |
|  | is the natural frequency of the structure; approximate values may be determined using Annex I. The limit of , where , corresponds to a peak factor of . |
|  | is the averaging time for the mean wind velocity, seconds*.* |

* 1. Non-constant sign mode shapes — Calculation of equivalent static wind force

(1) The procedure for calculating background and resonance response factor for the along-wind dynamic response for non-constant sign mode shapes should be taken from Table F.2.

Table F.2 — Calculation procedure for determination of the along-wind dynamic response

| Parameter | Subject reference |
| --- | --- |
| Structures covered by the procedure | F.9.1  Figure F.14 |
| Background response factor | F.9.2 Table F.3 |
| Resonance response factor | F.9.2 Table F.3 |
| Maximum amplitude of the fluctuating wind force | F.9.2 (F.21) |
| Maximum value of the equivalent static wind force | F.9.2 (F.20) |

* + 1. Structures covered by the procedure

|  |  |
| --- | --- |
| **e. Horizontal structures such as bridges supported in one central point.** | |
| Ein Bild, das Entwurf, Zeichnung, Diagramm, Reihe enthält.  Automatisch generierte Beschreibung | Ein Bild, das Entwurf, Diagramm, Reihe, Zeichnung enthält.  Automatisch generierte Beschreibung |
|  | Reference response: Torsional moment at support top |
| **f. Horizontal structures such as bridges supported in three points.** | |
| Ein Bild, das Entwurf, Zeichnung, Diagramm, Lineart enthält.  Automatisch generierte Beschreibung | Ein Bild, das Entwurf, Zeichnung, Diagramm, Reihe enthält.  Automatisch generierte Beschreibung |
|  | Reference response: Bending moment at mid-point of each span |

Key

|  |  |
| --- | --- |
| 1 | *F*w,f |

Figure F.14 — Structural dimensions and reference heights for structures where

* + 1. Calculation of equivalent static wind force and accelerations

(1) The maximum value of the equivalent static wind force per unit length of structures with non-constant sign mode shapes should be taken from Formula (F.20).

|  |  |
| --- | --- |
|  | (F.20) |

where

|  |  |
| --- | --- |
|  | is the mean wind force and should be taken as defined in 7.5 (5); |
|  | is the spatial and time-wise maximum amplitude of the fluctuating wind load, see Formula (F.21) and Figure F.14; |

|  |  |
| --- | --- |
|  | (F.21) |

where

|  |  |
| --- | --- |
|  | is the reference height, see Figure F.14; |
|  | is the load distribution factor for background turbulence and should be taken as defined in Table F.3; |
|  | is the load distribution factor for resonant turbulence and should be taken as defined in Table F.3; |
| and , , , and follow the definitions in F.5.3, and should be taken as defined in Figure F.14.. and follow the definitions in F.5.3. | |

NOTE The Value of is 3,5 unless the National Annex gives a different value.

(2) Accelerations are calculated by Formula (F.7) with and as specified in Table F.3.

(3) The span-wise admittance functions for non-constant sign static influence lines and mode shapes being cantilever and sinusoid are given by Formula (F.22) and (F.23) and shown in Figure F.15:

|  |  |  |
| --- | --- | --- |
| Non-constant sign: |  | (F.22) |
| (F.23) |

where is should be taken as defined in F.5.5.

Ein Bild, das Diagramm, Reihe, parallel, Muster enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | cantilever |
| 2 | full sinusoid |

Figure F.15 — Span-wise admittance functions

(4) The background response factor , which models the lack of correlation of the pressures on the structure surfaces is illustrated in Table F.3.

(5) The resonance response factor , that models turbulence in resonance with the considered vibration mode of the structure is illustrated in Table F.3.

Table F.3 — Static influence lines illustrations with background response factor , non-dimensional background size parameters and and load distribution factors . Mode shape illustrations with resonance response factor , non-dimensional resonance size parameters and and load distribution factors . is the structural response moment induced by the wind actions

| Structures in Figure F.14 | e. Cantilever | f. Simply supported |
| --- | --- | --- |
| **Static influence lines for background response** | Ein Bild, das Reihe, Diagramm enthält.  Automatisch generierte Beschreibung | Ein Bild, das Entwurf, Diagramm, Reihe, Zeichnung enthält.  Automatisch generierte Beschreibung |
|  |  |  |
|  |  |  |
|  | Formula (F.11) | Formula (F.11) |
|  |  | 1 |
| **Mode shape for resonant response** | Ein Bild, das Reihe, parallel, Antenne enthält.  Automatisch generierte Beschreibung | Ein Bild, das Reihe, Entwurf, Zeichnung, Schwarzweiß enthält.  Automatisch generierte Beschreibung |
|  |  |  |
|  |  |  |
|  | Formula (F.16) | Formula (F.16) |
|  | 3 | 2 |

NOTE For non-constant-sign mode shape cases the total mass of the vibrating structure is equal to times the modal mass.

* 1. Number of loads for dynamic response

(1) Figure F.16 shows the number of times , that the value of an effect of the wind is reached or exceeded during a period of 50 years. is expressed as a percentage of the value , where is the effect due to a 50 year return period wind action.

Ein Bild, das Reihe, Diagramm, parallel enthält.

Automatisch generierte Beschreibung

Figure F.16 — Number of gust loads for an effect during a 50 years period

The relationship between and should be taken from Formula (F.24):

|  |  |
| --- | --- |
|  | (F.24) |

(2) For fatigue damage calculations, the number of cycles at a particular proportion of the characteristic wind pressure may be estimated from Figure F.17 and Table F.4. is subdivided arbitrarily into twenty “5 %” bins and the number of cycles in each bin determined using Formula (F.24) to calculate the difference between the number of gust loads exceeded by the upper and lower limit. This approach may be used for linear, non-Reynolds number dependent structures.

Ein Bild, das Text, Diagramm, Reihe, Schrift enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| Y | number of cycles |

Figure F.17 — Number of cycles for an effect

Table F.4 — Number of cycles for an effect

| bin [%] | Number of cycles [–] |
| --- | --- |
| 0–5 |  |
| 5–10 |  |
| 10–15 |  |
| 15–20 |  |
| 20–25 |  |
| 25–30 |  |
| 30–35 |  |
| 35–40 |  |
| 40–45 |  |
| 45–50 |  |
| 50–55 |  |
| 55–60 |  |
| 60–65 |  |
| 65–70 |  |
| 70–75 |  |
| 75–80 |  |
| 80–85 |  |
| 85–90 |  |
| 90–95 |  |
| 95–100 |  |

1. (informative)  
     
   Procedure for across-wind and torsional actions on susceptible buildings
   1. Use of this annex

(1) This Informative Annex contains additional provisions to Clause 9 (1) specifying procedures for the evaluation of across-wind and torsional actions on buildings, as well as the corresponding response accelerations.

NOTE National choice on the application of this Informative Annex is given in the National Annex. If the National Annex contains no information on the application of this Informative Annex, it can be used.

* 1. Scope and field of application

(1) This Informative Annex applies to buildings with rectangular plan.

* 1. General

(1) In general, wind exerts along-wind, across-wind and torsional actions on buildings. Across-wind and torsional actions become more important, the higher, slenderer and more flexible the building is, mainly because of effects of flow separation.

(2) This Annex contains procedures applicable to rectangular plan buildings, unless the National Annex gives different procedures for use in the Country.

(3) The effects of across-wind and torsional actions should be assessed in accordance with this Annex if:

|  |  |
| --- | --- |
|  | (G.1) |

where *b*, *d*, *h* are the width, depth and height of the building (see Figure G.1). For buildings with greater than 8, the approach of Annex H.4 and H.5 should be used. For buildings with in the range of 6 to 8 the most onerous response according Annex G and Annex H should be used.

NOTE Across-wind effects dominate for nearly square building plans, whereas torsional effects dominate for buildings with elongated rectangular plans.

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Figure G.1 — Key for rectangular plan buildings

(4) The procedures given below apply when:

* the wind direction is orthogonal to a face of the building (usually the most unfavourable case);
* the building has a vertical uniform mass distribution;
* the building plan dimensions are such that:

|  |  |
| --- | --- |
|  | (G.2) |
|  | (G.3) |

where

|  |  |
| --- | --- |
|  | is the mean wind velocity, evaluated at a height ; |
|  | is the first across-wind or the first torsional frequency. |

(5) For buildings meeting the requirements of Formulas (G.1) through (G.3), G.4 and G.5 contain two detailed calculation procedures to assess the equivalent static across-wind and torsional actions. G.4 contains a simplified conservative procedure to assess static equivalent across-wind and torsional actions for square plan buildings. G.7 contains a procedure for the evaluation of across-wind and torsional accelerations for use in serviceability assessments of buildings. G.8 contains criteria for combining along-wind, across-wind and torsional actions and their effects.

(6) The procedures contained in this Annex are based on the assumption that the vibration mode, either across-wind or in torsion, is linear.

(7) For buildings not meeting the requirements of Formulas (G.1) through (G.3), use should be made of reliable experimental, numerical and/or theoretical methods. For buildings where , see Annex H.

* 1. Detailed procedure for across-wind actions

(1) Across wind actions are caused by both oncoming wind turbulence and by self-induced turbulence, e.g. associated with vortex shedding. This Section contains a procedure for evaluating the equivalent static actions in the across-wind direction, the procedure is outlined in Table G.1.

Table G.5 — Calculation procedure for determination of the across-wind action

|  |  |
| --- | --- |
| Step | Operation |
| 1 | Evaluation of geometric parameters (Figure G.1) |
| 2 | Evaluation of the mean wind velocity (6.3.1) |
| 3 | Evaluation of dynamic parameters and (Annex I) |
| 4 | Evaluation of parameter  (Formula (G.9)) |
| 5 | Evaluation of parameters and (if ) (Formula (G.10)) |
| 6 | Evaluation of parameters and (if ) (Formula (G.11), Figure G.3) |
| 7 | Evaluation of parameter and (if ) (Formula (G.12), Figure G.4) |
| 8 | Evaluation of parameter (Formula (G.8)) |
| 9 | Evaluation of resonant response factor (Formula (G.7)) |
| 10 | Evaluation of peak factor (Formula (G.13)) |
| 11 | Evaluation of dynamic coefficient (Formula (G.6)) |

(2) The equivalent across-wind static action per unit length should be taken from Formula (G.4):

|  |  |
| --- | --- |
|  | (G.4) |

where

|  |  |  |
| --- | --- | --- |
|  | is the mean velocity pressure, evaluated at height ; | |
|  | is the force coefficient associated with the fluctuating overturning moment in the across-wind plane (Figure G.2) given by Formula (G.5): | |
|  |  | (G.5) |
|  | is the across-wind dynamic factor, given by Formula (G.6): | |
|  |  | (G.6) |

where

|  |  |
| --- | --- |
|  | is the across-wind peak factor; |
|  | is the across-wind resonant response factor; |

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Figure G.2 — Force coefficient

(3) The resonant response factor in the across-wind direction should be taken from Formulae (G.7) through (G.12):

|  |  |
| --- | --- |
|  | (G.7) |

where

|  |  |  |
| --- | --- | --- |
|  | is the normalized spectrum of the across-wind action: | |
|  |  | (G.8) |
|  |  | (G.9) |

and , , and are the parameters given below:

|  |  |
| --- | --- |
|  | (G.10) |
|  | (G.11) |
|  | (G.12) |

where

|  |  |
| --- | --- |
|  | is the logarithmic decrement of structural damping in the first across-wind mode; |
|  | is the first across-wind frequency; |
| , | are dimensionless coefficients given in Figure G.3; |
| , | are the main across-wind excitation frequency and flow reattachment frequency, which are given in Figure G.4 in dimensionless format. |

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Figure G.3 — Parameters and

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Figure G.4 — Values of and

(4) The across-wind peak factor should be taken from Formula (G.13):

|  |  |
| --- | --- |
|  | (G.13) |

where

|  |  |
| --- | --- |
|  | is the mean wind velocity averaging time interval, . |

* 1. Detailed procedure for torsional actions

(1) Torsional actions are caused by the lateral turbulence and by the turbulent wake. This Section contains a procedure for evaluating the equivalent static torsional action; the procedure is outlined in Table G.2.

Table G.2 — Calculation procedure for determination of the torsional action

| Step | Operation |
| --- | --- |
| 1 | Evaluation of geometric parameters (Figure G.1) |
| 2 | Evaluation of the mean wind velocity (Section 6.3.1) |
| 3 | Evaluation of dynamic parameters and (Annex I) |
| 4 | Evaluation of parameter (Formula (G.19)) |
| 5 | Evaluation of parameters (if ≤ 6) and (if ≥ 4.5) (Formula (G.21), Figure G.6) |
| 6 | Evaluation of parameters (if ≤ 6) and (if ≥ 4.5) (Formula (G.22), Figure G.7) |
| 7 | Evaluation of parameters (if ≤ 6) and (if ≥ 4.5) (Formula (G.20)) |
| 8 | Evaluation of parameter (Formula (G.18)) |
| 9 | Evaluation of the resonant response factor (Formula (G.17)) |
| 10 | Evaluation of peak factor (Formula (G.23)) |
| 11 | Evaluation of dynamic coefficient (Formula (G.17)) |

(2) The equivalent torsional static action per unit length should be taken from Formula (G.14):

|  |  |
| --- | --- |
|  | (G.14) |

where

|  |  |
| --- | --- |
|  | is the mean velocity pressure evaluated at height ; |

*cM* is the moment coefficient associated with the fluctuating base torque (Figure G.5), given by Formula (G.15):

|  |  |
| --- | --- |
|  | (G.15) |

*cdM* is the torsional dynamic factor given by Formula (G.16):

|  |  |
| --- | --- |
|  | (G.16) |

where

|  |  |
| --- | --- |
|  | is the torsional peak factor; |
|  | is the torsional resonant response factor; |

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Figure G.5 — Moment coefficient

(3) The torsional resonant response factor should be taken from Formulae (G.17) to (G.22):

|  |  |
| --- | --- |
|  | (G.17) |
|  | (G.18) |
|  | (G.19) |
|  | (G.20) |
|  | (G.21) |
|  | (G.22) |

where

|  |  |
| --- | --- |
|  | is the logarithmic decrement of structural damping in the first torsional mode; |
|  | is the first torsional frequency; |
|  | is the larger value between and ; |
|  | is the mean wind velocity evaluated at height ; |
|  | is the reduced mean velocity, evaluated at height ; |
|  | are dimensionless coefficients given in Figure G.6; |
|  | are dimensionless coefficients given in Figure G.7. |



Figure G.6 — Dimensionless coefficients and

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Figure G.7 — Dimensionless coefficients and

(4) The torsional peak factor should be taken from Formula (G.23):

|  |  |
| --- | --- |
|  | (G.23) |

where

|  |  |
| --- | --- |
|  | is the mean wind velocity averaging time interval, ; |

* 1. Simplified procedure for across-wind and torsional actions for square plan buildings

(1) Using the procedure of G.4 and G.5, conservative values of the across-wind and torsional dynamic factors may be derived for square plan buildings with regular distribution of stiffness and mass. The figures reported in this Section were obtained using the detailed procedure, as an envelope for all possible situations associated with different values of the fundamental basic wind velocity and of the roughness length, assuming a unit value for the orography factor.

(2) The value of the across-wind and torsional dynamic factors apply to square buildings satisfying Formulas (G.1) and (G.3), therefore buildings with .

(3) Figure G.8 and Figure G.9 show the across-wind dynamic factor for steel buildings and for reinforced concrete or composite buildings, respectively. The shaded areas in the figures indicate situations in which it is not strictly necessary to assess the effects of across-wind actions, as (Formula (G.1)).

(4) Figure G.10 and Figure G.11 show the torsional dynamic factor for steel buildings and for reinforced concrete or composite buildings, respectively. The shaded areas in these figures indicate situations in which it is not strictly necessary to assess the effects of torsional actions, as (Formula (G.1)).

Dimensions *b* and *h* in metres

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Figure G.8 — Values for the across-wind dynamic factor for square plan steel buildings

Dimensions *b* and *h* in metres



Figure G.9 — Values for the across-wind dynamic factor for square plan reinforced concrete or composite buildings

Dimensions *b* and *h* in metres

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Figure G.10 — Values for the torsional dynamic factor for square plan steel buildings

Dimensions *b* and *h* in metres

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Automatisch generierte Beschreibung

Figure G.11 — Values for the torsional dynamic factor for square plan reinforced concrete or composite buildings

* 1. Across-wind and torsional accelerations

The peak value of the across-wind acceleration at height *z* of the building should be taken from Formula (G.24):

|  |  |
| --- | --- |
|  | (G.24) |

where

|  |  |  |
| --- | --- | --- |
|  | is the across-wind peak factor, Formula (G.13); | |
|  | is the standard deviation of the across-wind acceleration at height : | |
|  |  | (G.25) |

where

|  |  |  |
| --- | --- | --- |
|  | is the air density; | |
|  | is the mean wind velocity evaluated at *z*=*h*, for the return period used for serviceability assessments; | |
|  | is the width of the building (Figure G.1); | |
|  | is the height of the building (Figure G.1); | |
|  | is the generalised mass of the building in the first across-wind mode: | |
|  |  | (G.26) |
|  | is the building mass per unit height; | |
|  | is the aerodynamic force coefficient, Formula (G.5); | |
|  | is the across-wind resonant response factor, the square of which should be taken from Formula (G.7), for the return period used for serviceability assessments; | |
|  | is the first across-wind mode shape. | |

The peak value of the torsional acceleration at height *z* of the building should be taken from Formula (G.27):

|  |  |
| --- | --- |
|  | (G.27) |

where

|  |  |  |
| --- | --- | --- |
|  | is the torsional peak factor, Formula (G.21); | |
|  | is the standard deviation of the angular acceleration at height *:* | |
|  |  | (G.28) |

where

|  |  |  |
| --- | --- | --- |
|  | is the air density; | |
|  | is the mean wind velocity, evaluated at , for the return period used for serviceability assessments; | |
|  | is the width of the building (Figure G.1); | |
|  | is the height of the building (Figure G.1); | |
|  | is the generalised polar mass moment of inertia of the building in the first torsional mode: | |
|  |  | (G.29) |
|  | is the building polar mass moment of inertia per unit height; | |
|  | is the torsional moment aerodynamic coefficient, Formula (G.15); | |
|  | is the torsional resonant response factor, the square of which should be taken from Formula (G.17), for the return period used for serviceability assessments; | |
|  | is the first torsional mode shape. | |

* 1. Combination of actions and action effects

(1) Across-wind and torsional actions should be combined with each other and with along-wind actions. Similarly, the associated effects have to be combined (e.g. displacements, rotations, stress resultants, accelerations).

(2) The three combination rules given in Table G.1 should be used.

Table G.1 — Combination rules for action effects for each wind direction

| Combination | Along-wind action effects | Across-wind action effects | Torsional action effects |
| --- | --- | --- | --- |
| 1 | *D* |  |  |
| 2 |  | *L* |  |
| 3 |  |  | *M* |

The symbols in Table G.1 have the following meanings:

|  |  |  |
| --- | --- | --- |
| *D*, *L*, *M* | indicate an along-wind, across-wind or torsional action or action effects, respectively; | |
|  |  | (G.30) |
|  | is the along-wind gust factor; | |
| γ*LM* | is the dimensionless combination coefficient of across-wind and torsional actions and action effects, given in Table G.2. | |

Table G.2 — Combination coefficients of and

|  |  |  | | |
| --- | --- | --- | --- | --- |
|  |  |  |
| ≤ 0,5 | 0,1 | 0,95 | 0,61 | 0,55 |
| 0,2 | 0,55 | 0,67 | 0,61 |
| 0,3 | 0,55 | 0,73 | 0,67 |
| 0,6 | 0,79 | 0,79 | 0,79 |
| ≥ 1 | 0,84 | 0,84 | 0,84 |
| 1 | ≤ 0,1 | 0,84 | 0,55 | 0,55 |
| 0,2 | 0,61 | 0,55 | 0,55 |
| 0,3 | 0,55 | 0,55 | 0,55 |
| 0,6 | 0,67 | 0,67 | 0,67 |
| ≥ 1 | 0,73 | 0,73 | 0,73 |
| ≥ 2 | ≤ 0,05 | 0,79 | 0,55 | 0,55 |
| ≥ 0,1 | 0,55 | 0,55 | 0,55 |

The symbols in Table G.2 have the following meanings:

|  |  |  |
| --- | --- | --- |
|  | is the lowest frequency between and ; | |
|  | is the ratio between the across-wind and torsional frequencies: | |
|  |  | (G.31) |

Linear interpolation may be used for intermediate values between those given in Table G.2.

1. (informative)  
     
   Procedure for across-wind dynamic and aeroelastic response of slender structures
   1. Use of this annex

(1) This Informative Annex provides complementary/supplementary guidance to 10 for specifying the effects of aeroelastic phenomena.

NOTE National choice on the application of this Informative Annex is given in the National Annex. If the National Annex contains no information on the application of this informative annex, it can be used.

* 1. Scope and field of application

(1) This Informative Annex applies to bridges, towers, masts, chimneys and other engineering structures. It also applies to buildings when the conditions specified in 9(3) and 9(4) are met.

(2) This Informative Annex does not apply to structures with significant longitudinal variation of the shape or across-wind dimension.

* 1. General

(1) The procedures for across-wind dynamic and aeroelastic response of slender structures cover:

* Across-wind dynamic response due to turbulence of the incoming air flow, see H.4;
* Vortex-induced vibrations due to vortices shed alternately from opposite sides of the structure, see H.5;
* Galloping-induced vibrations due to negative aerodynamic damping, see H.6;
* Divergence and flutter-induced vibrations due to aerodynamic instabilities, see H.7.

Annex H applies to slender structures with length exceeding , where is the width and is the depth of the structure in the direction of the wind action. H.4 applies to structures, where the critical wind velocity for across-wind bending vibrations is less than 0,75 times the characteristic mean wind velocity. H.5-H.7 should be considered for all slender structures.

NOTE H.4 is not relevant for buildings covered by prEN 1991‑1‑4. H.4 can be applicable for bridges or engineering structures.

(2) Annex H applies for wind directions perpendicular to the main axis of the structure. Non-perpendicular wind directions will normally give a smaller structural response.

(3) Across-wind dynamic response in H.4 and vortex-induced vibrations in H.5 should not be combined. Their maximum response values occur at different wind velocities and thereby not simultaneously.

(4) It is assumed that either the along-wind dynamic response or the across-wind response are dominating and that the responses not need to be combined.

NOTE The National Annex can give additional guidance on combinations of along-wind dynamic response and across-wind response.

* 1. Across-wind dynamic response
     1. General

(1) The procedure for calculating the across-wind dynamic response of slender structures given in Table H.1 should be applied.

Table H.1 — Calculation procedure for determination of the along-wind dynamic response

| Parameter | Subject reference |
| --- | --- |
| Resonance response factor | H.4.5 (H.8) and H.4.6 (H.11) |
| Characteristic across-wind peak acceleration | H.4.3 (H.1) |
| Peak value of the equivalent static wind load per unit length of structures | H.4.3 (H.3) |

* + 1. Mode shapes

(1) The procedure for across-wind dynamic response may be used for structures where only one dominant mode is significant for the vibrations of the structure. General shapes of structures covered by the procedure are shown in Figure H.1 and Figure H.2.

NOTE The contribution to the response from the second or higher order across-wind vibration modes is assumed negligible.

|  |  |
| --- | --- |
| **a) Vertical structures such as buildings.** | |
| Ein Bild, das Entwurf, Zeichnung, Diagramm, Design enthält.  Automatisch generierte Beschreibung | Ein Bild, das Entwurf, Zeichnung, Design, Schwarzweiß enthält.  Automatisch generierte Beschreibung |
|  | Equivalent static wind force |
| **b) Horizontal structures such as bridges supported in two points.** | |
| Ein Bild, das Entwurf, Zeichnung, Diagramm, technische Zeichnung enthält.  Automatisch generierte Beschreibung | Ein Bild, das Entwurf, Zeichnung, Darstellung, Design enthält.  Automatisch generierte Beschreibung |
|  | Equivalent static wind force |

Figure H.1 — The structural dimensions and reference heights for structures where used in the procedure for across-wind dynamic response for cases a) and b)

|  |  |
| --- | --- |
| **c) Horizontal structures such as bridges supported in one point.** | |
| Ein Bild, das Entwurf, Diagramm, Reihe, Zeichnung enthält.  Automatisch generierte Beschreibung | Ein Bild, das Entwurf, Zeichnung, Reihe, Diagramm enthält.  Automatisch generierte Beschreibung |
|  | Equivalent static wind force |
| **d) Horizontal structures such as bridges supported in three points.** | |
| Ein Bild, das Entwurf, Diagramm, Zeichnung, technische Zeichnung enthält.  Automatisch generierte Beschreibung | Ein Bild, das Entwurf, Zeichnung, Darstellung, Design enthält.  Automatisch generierte Beschreibung |
|  | Equivalent static wind force |

Figure H.2 — The structural dimensions and reference heights for structures where used in the procedure for across-wind dynamic response for cases c) and d)

* + 1. Calculation of structural across-wind acceleration and equivalent static force

(1) The characteristic across-wind peak acceleration of the structural point with coordinate along the structural main axis is approximately given by Formula (H.1):

|  |  |
| --- | --- |
|  | (H.1) |

where

|  |  |
| --- | --- |
|  | is the reference height, see Figure H.1 and Figure H.2; |
|  | is the peak factor for resonance response defined as the ratio of the expected maximum value over 10 minutes of the fluctuating resonant response to its standard deviation, see Formula (H.2); |
|  | is the across-wind force coefficient and should be taken equal to as defined in Table H.7. For a flat plate with wind perpendicular to the plate axis and along the plate, ; |
|  | is the turbulence intensity for across-wind fluctuations and should be taken as defined in Figure H.4.The reference height is given in Figure H.1 and Figure H.2. and for horizontal and vertical across-wind vibrations, respectively; |
|  | is the characteristic mean velocity pressure and should be taken as defined in 6.3.1(3), Formula (6.5); |
|  | is the depth of the structure and should be taken as defined in Figure H.1 and Figure H.2; |
|  | is the resonance response factor, accounting for turbulence in resonance with the vibrations of the structure and should be taken as defined in H.4.5(1), Formula (H.8) or H.4.6(1), Formula (H.11), as appropriate; |
|  | is the load distribution factor and should be taken as defined in Table H.2. It is the total mass divided by the modal mass for a mode shape normalized to 1 in the point with maximum amplitude; |
|  | is the reference mass per unit length and should be taken as defined in I.6, Formula (I.18); |
|  | is the mode shape; |
|  | is the mode shape value at the point with maximum amplitude. |

Table H.2— Load distribution factors

| Structures in  Figure H.1 and  Figure H.2 | a. | b. | c. | d. |
| --- | --- | --- | --- | --- |
| Linear | Half sinusoid | Cantilever | Simply supported |
|  | 3 | 2 | 3 | 2 |

(2) The peak factor for resonant response, defined as the ratio of the expected maximum value over 10 minutes of the fluctuating resonant response to its standard deviation, should be obtained from Formula (H.2):

|  |  |
| --- | --- |
|  | (H.2) |

where

|  |  |
| --- | --- |
|  | is the natural frequency of the structure equal to and for horizontal and vertical across-wind vibrations, respectively; |
|  | is the averaging time for the mean wind velocity, seconds*.* |

(3) The peak value of the equivalent static wind load per unit length of structures is given in Formula (H.3).

|  |  |
| --- | --- |
|  | (H.3) |

where is the vibrating mass of the structure per unit length [kg/m], should be taken as defined in H.4.5(1), Formula (H.8) or H.4.6(1), Formula (H.11) and is the mean wind load in the across-wind direction.

NOTE 1 It is on the safe side to use .

NOTE 2 For the structure shown in Figure H.1 and Figure H.2, the mean wind load in the across-wind direction .

* + 1. Across-wind turbulence

(1) The across-wind turbulence intensity and should be taken as defined in Figure H.4.

(2) The wind velocity distribution over frequencies is expressed by the one-sided non-dimensional power spectral density function and for lateral and vertical turbulence, respectively and should be determined using Formula (H.4) and (H.5):

|  |  |
| --- | --- |
|  | (H.4) |
|  | (H.5) |

where the non-dimensional frequencies and should be determined using Formula (H.6) and (H.7), respectively

|  |  |
| --- | --- |
|  | (H.6) |
|  | (H.7) |

where

|  |  |
| --- | --- |
|  | is the natural frequency of the structure in Hz for the mode shown in  Figure H.1 and  Figure H.2; |
|  | is the characteristic mean wind velocity and should be taken as defined in 6.3.1, Formula (6.4); |
|  | is the lateral turbulence length scale for vertical structures; |
|  | is the vertical turbulence length scale for horizontal structures. |

NOTE The along-wind power spectral density function is given in F.4 (2). The turbulent length scale is defined in F.4 (1) (F.3).

The power spectral density function is illustrated in Figure H.3 where the non-dimensional frequency is  *or*  and the one-sided non-dimensional power spectral density function is or for lateral and vertical turbulence, respectively.

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Figure H.3 — Power spectral density function

| **Vertical structure** | | **Horizontal structure** | |
| --- | --- | --- | --- |
| Ein Bild, das Entwurf, Zeichnung, Diagramm, Design enthält.  Automatisch generierte Beschreibung | | Ein Bild, das Entwurf, Zeichnung, Diagramm, technische Zeichnung enthält.  Automatisch generierte Beschreibung | |
| One-sided non-dimensional power spectral density function | Turbulence intensity | One-sided non-dimensional power spectral density function | Turbulence intensity |
| NOTE The turbulence intensity is defined in 6.4. | | | |

Key

|  |  |
| --- | --- |
| 1 | wind |
| 2 | cross-sectional admittance |
| 3 | correlation of wind |

Figure H.4 — Wind characteristics

* + 1. Resonance response factor for constant sign mode shapes

(1) For structures in Figure H.1 the resonance response factor allowing for turbulence in resonance with the considered vibration mode of the structure is given in Formula (H.8) using the non-dimensional resonance size parameters given in Formula (H.9) and Formula (H.10):

|  |  |
| --- | --- |
|  | (H.8) |
|  | (H.9) |
|  | (H.10) |

where

|  |  |
| --- | --- |
|  | is the total logarithmic decrement of damping and should be taken as defined in in I.7 (1); |
|  | is the non-dimensional power spectral density function and should be taken as given in Figure H.4; |
|  | is the cross-sectional resonance admittance function taking into account the lack of correlation of pressures acting in a cross-section at the natural frequency. and should be taken as defined in Formula (F.9); |
|  | is the span-wise resonance admittance function taking into account the lack of correlation of forces acting along the length of the structure at the natural frequency. should be taken as defined in Formula (F.9); |
|  | is the non-dimensional cross-sectional resonance size parameter; |
|  | is the non-dimensional span-wise resonance size parameter. |

and should be taken as defined in Figure H.4. The characteristic mean wind velocity is given in 6.3.1(1), Formula (6.4) and the frequency .

NOTE 1 is an upper value of the cross-sectional admittance function and it is determined by correlations of the incoming, undisturbed air flow using the non-dimensional cross-sectional resonance size parameter.

NOTE 2 is an approximation of the span-wise admittance function and it is determined by correlations of the incoming, undisturbed air flow using the non-dimensional span-wise resonance size parameter.

* + 1. Resonance response factor for non-constant sign mode shapes

(1) For structures in

Figure H.2 the resonance response factor allowing for turbulence in resonance with the considered vibration mode of the structure should be taken as defined in Formula (H.11) using the non-dimensional resonance size parameters given in Formula (H.12) and (H.13):

|  |  |
| --- | --- |
|  | (H.11) |
|  | (H.12) |
|  | (H.13) |

where

|  |  |
| --- | --- |
|  | is the cross-sectional resonance admittance function taking into account the lack of correlation of pressures acting in a cross-section at the natural frequency. should be taken as defined in Formula (F.9); |
|  | is the span-wise resonance admittance function taking into account the lack of correlation of forces acting along the length of the structure at the natural frequency. should be taken as defined in Formula (F.22) or Formula (F.23). |

* 1. Vortex shedding
     1. General

(1) Vortex shedding occurs when vortices are shed alternately from opposite sides of the structure. This gives rise to a fluctuating load typically giving vibrations perpendicular to the mean wind direction. Depending on the structures configuration, different modes and deviating vibration directions may occur. Resonant vibrations may occur if the frequency of vortex shedding is the same or similar to a natural frequency of the structure. This condition occurs when the wind velocity is equal to the critical wind velocity should be taken as defined in H.3.3.1. Critical wind velocities may occur frequently and may cause significant high-cycle fatigue damage. When it occurs at high wind speeds failure may be via plastic fatigue.

(2) The response induced by vortex shedding is composed of broad-banded response that occurs whether or not the structure is moving, and narrow-banded response originating from motion-induced wind load.

NOTE 1 Broad-banded response is normally most important for reinforced concrete buildings and bridges, and heavy steel structures.

NOTE 2 Narrow-banded response is normally most important for light steel structures, e.g. buildings and bridges.

(3) The approach given in H.5 may be applied for structures with a regular distribution of cross-section dimensions. For structures with varying width and depth of the cross-section, the dimensions at the point with largest displacements in the mode considered are used.

* + 1. Criteria for vortex shedding

(1) The effect of vortex shedding should be considered when . The dimensions , and should be taken as defined in Figure H.1 and Figure H.2.

(2) The effect of vortex shedding may be neglected when

|  |  |
| --- | --- |
|  | (H.14) |

where

|  |  |
| --- | --- |
|  | is the critical wind velocity for mode and should be taken as defined in H.5.3.1; |
|  | is the characteristic 10-minutes mean wind velocity specified in 6.3.1 (1) at the cross-section where the largest displacement occurs. |

NOTE The factor 1,25 covers uncertainties in the evaluation of and the risk of wind velocities being larger than the characteristic value.

* + 1. Basic parameters for vortex shedding
       1. Critical wind velocity

(1) The critical wind velocity for bending vibration of mode is defined as the wind velocity at which the frequency of vortex shedding equals the natural frequency (mode ) of the structure or structural element and is given in Formula (H.15).

|  |  |
| --- | --- |
|  | (H.15) |

where

|  |  |
| --- | --- |
|  | is the reference width of the cross-section at which resonant vortex shedding occurs and where the modal deflection is maximum for the structure or structural part considered. For circular cylinders the reference width is the outer diameter; |
|  | is the natural frequency of the considered bending mode  of across-wind vibration. Approximations for are given in I.4; |
|  | Strouhal number and should be taken as defined in H.5.3.2. |

(2) The critical wind velocity for ovalling vibration in mode  of cylindrical shells is defined as the wind velocity at which two times of the frequency of vortex shedding equals a natural frequency of the ovalling mode  of the cylindrical shell and should be taken as defined in Formula (H.16).

|  |  |
| --- | --- |
|  | (H.16) |

where

|  |  |
| --- | --- |
|  | is the outer shell diameter; |
|  | is the Strouhal number and should be taken as defined in H.3.3.2; |
|  | is the natural frequency of the ovalling mode of the shell. |

For shells without stiffening rings should be taken as defined in I.4 (6).

NOTE  Procedures to calculate ovalling vibrations are not covered in Annex H. Inclusion of stiffening rings can increase the critical wind velocity sufficiently to fulfil the requirements in Formula (H.14).

* + - 1. Strouhal number

(1) The Strouhal number for different cross-sections may be taken from Table H.3.

Table H.3 — Strouhal numbers for different cross-sections

| Cross-section | |  |
| --- | --- | --- |
| Ein Bild, das Diagramm, Reihe, Kreis, Entwurf enthält.  Automatisch generierte Beschreibung  for all -numbers |  | from Figure H.5 |
| Ein Bild, das Diagramm, Reihe enthält.  Automatisch generierte Beschreibung |  | from Figure H.6 |
| Ein Bild, das Diagramm, Reihe, technische Zeichnung, Design enthält.  Automatisch generierte Beschreibung  linear interpolation |  | 0,11 |
|  | 0,10 |
|  | 0,14 |
| Ein Bild, das Diagramm, Reihe, Entwurf, technische Zeichnung enthält.  Automatisch generierte Beschreibung  linear interpolation |  | 0,13 |
|  | 0,08 |
| Ein Bild, das Diagramm, Reihe, technische Zeichnung enthält.  Automatisch generierte Beschreibung  linear interpolation |  | 0,16 |
|  | 0,12 |
| Ein Bild, das Diagramm, Reihe, technische Zeichnung enthält.  Automatisch generierte Beschreibung  linear interpolation |  | 0,11 |
|  | 0,07 |
| Extrapolations for Strouhal numbers as function of are not allowed. | | |

Ein Bild, das Diagramm, Reihe enthält.

Automatisch generierte Beschreibung

Figure H.5 — Strouhal number () for circular cross-sections as a function of Reynolds number should be taken as defined in H.5.3.3

Ein Bild, das Diagramm, technische Zeichnung, Reihe, Plan enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | range of Strouhal numbers |
| For the Strouhal number is particularly uncertain, and vortex- and galloping-induced vibrations may couple. | |

Figure H.6 — Strouhal number () for rectangular cross-sections with sharp corners

(2) The design should consider the most onerous value shown in the range.

NOTE 1 The range of Strouhal numbers for indicates dependencies on turbulence, vibration amplitudes, Reynolds number, etc. For   1,5< *d/b* <2,5, the Strouhal number is particularly uncertain, and vortex- and galloping-induced vibrations can couple.

NOTE 2 The National Annex can give further information on the Strouhal number.

* + - 1. Reynolds number

(1) The vortex shedding action on a circular cylinder depends on the Reynolds number at the critical wind velocity . The Reynolds number should be taken as defined in Formula (H.17).

|  |  |
| --- | --- |
|  | (H.17) |

where

|  |  |
| --- | --- |
|  | is the kinematic viscosity of the air ( m2/s). |

NOTE The Reynolds number is discussed in 7.1 (2).

* + - 1. Generalised Scruton number

(1) The susceptibility of vibrations depends on the structural damping and the ratio of structural mass to fluid mass. This is expressed by the generalised Scruton number , which should be taken as defined in Formula (H.18).

|  |  |
| --- | --- |
|  | (H.18) |

where

|  |  |
| --- | --- |
|  | is the structural damping expressed by the logarithmic decrement should be taken as defined in I.7 (2), Table I.3; |
|  | is the air density under vortex shedding conditions; |
|  | is the equivalent mass per unit length for mode and should be taken as defined in  I.6 (1); |
|  | is the reference width of the cross-section at which resonant vortex shedding occurs; |
|  | is the reference depth of the cross-section at which resonant vortex shedding occurs. |

NOTE 1 The value of the air density is 1,25 kg/m3 unless the National Annex gives a different value.

NOTE 2 Limiting values of the generalized Scruton Number for the use of H.4 and H.5 can be provided by the National Annex.

* + 1. Vortex shedding action

(1) The effect of vibrations induced by vortex shedding should be calculated from the effect of the inertia force per unit length *,* acting perpendicular to the wind direction at location *s* on the structure and should be taken as defined in Formula (H.19):

|  |  |
| --- | --- |
|  | (H.19) |

where

|  |  |
| --- | --- |
|  | is the vibrating mass of the structure per unit length [kg/m]; |
|  | is the natural frequency of the structure in the across-wind direction; |
|  | is the mode shape of the structure in the across-wind direction normalised to 1 at the point with the maximum displacement; |
|  | is the maximum displacement over time of the point where equals 1, see H.5.5. |

The effect of rhythmic vortex shedding depends on the turbulence intensity of the wind. For mean wind velocities larger than approx. 15 m/s, the turbulence intensity of the wind is determined according to 6.4 (1).

(2) For mean wind velocities lower than approx. 10 m/s, consideration should be given to rhythmic vortex shedding in turbulence free wind which occurs under certain, relatively rare meteorological conditions. For mean wind velocities between 10 m/s and 15 m/s, the minimum turbulence intensity of the wind may be determined by linear interpolation.

NOTE The National Annex can define appropriate input parameters (like , turbulence intensity and velocity limits).

* + 1. Calculation of across-wind amplitude
       1. General

(1) The approach given in H.5.5.2 may be used to calculate the displacement in a mode for structures with a regular distribution of cross-section dimensions along the main axis of the structure. Typically structures covered are buildings, chimneys, masts and bridges. This approach allows for the consideration of different modes and turbulence intensities, depending on meteorological conditions. For regions where it is likely that it may become very cold and stratified flow conditions may occur (e.g. in coastal areas in Northern Europe), low turbulence conditions can become relevant.

NOTE The National Annex can give the regions where very cold and stratified flow conditions can occur.

* + - 1. Calculation procedure

(1) The characteristic maximum displacement at the point with the largest movement should be taken as defined in Formula (H.20).

|  |  |
| --- | --- |
|  | (H.20) |

where

|  |  |
| --- | --- |
|  | is the standard deviation of the displacement and should be taken as defined in H.5.5.2(2), Formula (H.21); |
|  | is the peak factor and should be taken as defined in H.5.5.3(1), Formula (H.24). |

(2) The standard deviation of the displacement at the point with the largest movement may be calculated by using Formula (H.21).

|  |  |
| --- | --- |
|  | (H.21) |

where

|  |  |
| --- | --- |
|  | is the aerodynamic load coefficient dependent on the cross-sectional shape and on the lift force acting on a non-moving structure, and for a circular cylinder also dependent on the Reynolds number which should be taken as defined in H.5.3.3 (1);   should be taken as defined in H.5.6, as appropriate; |
|  | is the aerodynamic damping parameter specifying the motion-induced wind loads and for a circular cylinder also dependent on the Reynolds number which should be taken as defined in H.5.3.3 (1);   should be taken as defined in H.5.6, as appropriate; |
|  | is an exponent controlling the aerodynamic damping curve, see NOTE 1; |
|  | is the normalised limiting amplitude giving the deflection of structures with very low damping specifying the motion-induced wind loads and should be taken as defined in H.5.6; |
|  | is the generalised Scruton number and should be taken as defined in H.5.3.2; |
|  | is the Strouhal number and should be taken as defined in Table H.3; |
|  | is the air density under vortex shedding conditions; |
|  | is the equivalent mass per unit length and should be taken as defined in I.6 (1); |
|  | is the effective length of the structure: , where the mode shape of the structure is normalised to 1 at the point with the maximum displacement; |
|  | is the length and across-wind width of structure. For structures with varying width, the width at the point with largest displacements is used. |

NOTE The National Annex can give further information on the exponent . If nothing else is recommended in the National Annex, use = 2.

(3) The aerodynamic parameters governing the response of the structure as illustrated in Figure H.7.

Ein Bild, das Diagramm, Text, Reihe enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
|  | *Sc*G < 4 ⋅ *π* ⋅ *K*a |
|  | *Sc*G > 4 ⋅ *π* ⋅ *K*a |
| 1 | motion-induced forces dominating |
| 2 | transition range |
| 3 | lift forces dominating |
| 4 | amplitude governed by *C*c |

Figure H.7 — Generalised Scruton number curve

NOTE 1 The value of the air density can be given in the National Annex. The recommended value is 1,25 kg/m3.

NOTE 2 Unless otherwise specified in the National Annex the Strouhal number , the aerodynamic constant , aerodynamic damping parameter and normalised limiting amplitude are given in H.3.6.

NOTE 3 It is good practice to ensure that generalised Scruton number , taking the uncertainties originating from structural damping into account, see Table I.2. The values of the normalising limiting amplitude are given for guidance and present only rough approximation of the order magnitude of the deflection for very low generalised Scruton numbers.

(4) The solution to Formula (H.22) is given in Formula (H.23).

|  |  |
| --- | --- |
|  | (H.22) |

where the constants and should be taken as defined by:

|  |  |
| --- | --- |
|  | (H.23) |

NOTE It has been assumed that .

* + - 1. Peak factor

(1) The peak factor should be taken from Formula (H.24) and illustrated in Figure H.8:

|  |  |
| --- | --- |
|  | (H.24) |

Ein Bild, das Diagramm, Reihe, Text, parallel enthält.

Automatisch generierte Beschreibung

Figure H.8 — Peak factor as a function of

* + 1. Aerodynamic parameters for single structures
       1. Circular cylinders

(1) For a circular cylinder the maximum values of the aerodynamic constants , , and of should be taken as defined in Table H.4.

Table H.4 — Aerodynamic constants for determination of the effect of vortex shedding

| Constant | Circular cylinder | Circular cylinder | Circular cylinder |
| --- | --- | --- | --- |
|  |  |  |  |
|  | 0,01 | 0,0025 | 0,005 |
|  | 2 | 0,5 | 1 |
|  | 0,4 | 0,4 | 0,4 |
| NOTE For circular cylinders the constants and are assumed to vary linearly with the logarithm of the Reynolds number for and for . | | | |

NOTE The National Annex can give additional guidance on the aerodynamic constants.

(2) The vibration of the structure is not underestimated if the dependence of the aerodynamic damping constant on the turbulence intensity is determined by the simplified and approximated Formula (H.25):

|  |  |
| --- | --- |
|  | (H.25) |

where

|  |  |
| --- | --- |
|  | is determined from for and for . The turbulence intensity is determined at the height above ground with the largest movement of the structure, see H.5.4 (2); |

* + - 1. Rectangular structures

(1) For rectangular structures the maximum values of the aerodynamic constants , , and of should be taken as defined in Table H.5.

Table H.5 — Aerodynamic constants for determination of the effect of vortex shedding as a function of

|  | 0,25‑1,25 | 3‑5 |
| --- | --- | --- |
|  | 0,03 | 0,03 |
|  | 6,0 | 3,0 |
|  | 0,60 | 0,10 |

NOTE The National Annex can give additional guidance on the aerodynamic constants. Interpolation between and is not allowed.

* + - 1. Number of load cycles

(1) The number of load cycles caused by vortex excited oscillation should be taken from Formula (H.26).

|  |  |
| --- | --- |
|  | (H.26) |

where

|  |  |
| --- | --- |
|  | is the natural frequency of across-wind mode [Hz]. Approximations for are given in Annex I; |
|  | is the critical wind velocity [m/s] and should be taken as defined in H.5.3.1; |
|  | is times the modal value of the Weibull probability distribution assumed for the wind velocity [m/s]; |
|  | is the design service life in seconds, which is equal to 3,2107 multiplied by the expected design service life in years; |
|  | is the bandwidth factor describing the band of wind velocities with vortex-induced vibrations, see Note 3. |

NOTE 1 The National Annex can specify the minimum value of . The recommended value is .

NOTE 2 The value can be taken as 20 % of the characteristic mean wind velocity as specified in 6.3.1 (1), Formula (6.4) at the height of the cross-section with largest displacement.

NOTE 3 The bandwidth factor is in the range 0,1 to 0,3. It can be taken as .

* + 1. Vertical cylinders in a row or grouped arrangement

(1) For circular cylinders in a row or grouped arrangement with or without coupling (see Figure H.9) vortex excited vibrations can occur.

Ein Bild, das Diagramm, Entwurf, Reihe, technische Zeichnung enthält.

Automatisch generierte Beschreibung

Figure H.9 — In-line and grouped arrangements of cylinders

(2) The maximum deflections of oscillation should be taken from Formula (H.20) and the calculation procedure should be taken from H.5.5.2 with the values specified by Formulas (H.27) and (H.28).

(3) For in-line, free standing circular cylinders without coupling:

|  |  |  |
| --- | --- | --- |
|  |  | (H.27) |
|  |  |
| Linear interpolation |  |
|  |  |
|  |  |

where

|  |  |
| --- | --- |
|  | is given in H.5.6.1; |
|  | is given in Table H.3. |

NOTE The factor for circular cylinders without coupling is a rough approximation. It is expected to be conservative.

(4) For coupled cylinders:

|  |  |
| --- | --- |
|  | (H.28) |

where

|  |  |
| --- | --- |
|  | is the interference factor for vortex shedding and should be taken as specified in Table H.6; |
|  | is the Strouhal number and should be taken as specified in Table H.6; |
|  | is the generalised Scruton number and should be taken as specified in Table H.6. |

For coupled cylinders with specialist advice is recommended.

Table H.6 — Data for the estimation of the interference factor for vortex shedding

| Coupled cylinders | Generalised Scruton number . is the equivalent mass per unit length including all coupled cylinders, see (H.18) and (H.17). | |
| --- | --- | --- |
|  |  |
| Ein Bild, das Diagramm, Entwurf, Kreis, Zeichnung enthält.  Automatisch generierte Beschreibung |  |  |
| Ein Bild, das Entwurf, Diagramm, Zeichnung, Design enthält.  Automatisch generierte Beschreibung |  |  |
| Ein Bild, das Diagramm, Reihe, Kreis, Design enthält.  Automatisch generierte Beschreibung |  |  |
|  | linear interpolation | |
| Ein Bild, das Diagramm, Reihe, Text enthält.  Automatisch generierte Beschreibung  Reciprocal Strouhal numbers of coupled cylinders with in-line and grouped arrangements | |

* + 1. Measures against vortex induced vibrations

(1) The vortex-induced amplitudes may be reduced by means of aerodynamic devices (only under special conditions, e.g. Scruton numbers larger than 8) or damping devices supplied to the structure. The drag coefficient for a structure with circular cross-section and aerodynamic devices based on the basic diameter , may increased up to a value of 1,4. Both applications require special advice.

* 1. Galloping
     1. General

(1) Galloping is a self-induced vibration of a flexible structure in across-wind bending mode. Non circular cross-sections including L-, I-, U- and T-sections are prone to galloping. Ice may cause a stable cross-section to become unstable.

(2) Single, free-standing circular cylinders with constant cross-section are not prone to galloping unless subject to accretion of asymmetric ice.

(3) Nominally circular cross-sections with minor deviations from an exact circular shape may experience galloping at Reynolds numbers around the transition between sub- and super-critical flow regimes, so-called dry galloping.

NOTE Sub- and super-critical flow regimes around circular cross-sections are defined in Annex E.

(4) Galloping oscillation starts at a special onset wind velocity and normally the amplitudes increase rapidly with increasing wind velocity.

* + 1. Onset wind velocity

(1) The onset wind velocity of galloping, , is given in Formula (H.29).

|  |  |
| --- | --- |
|  | (H.29) |

where

|  |  |
| --- | --- |
|  | is the generalised Scruton number and should be taken as defined in H.5.3.4(1); |
|  | is the across-wind fundamental frequency of the structure; approximations of are given in I.2; |
|  | is the width and should be taken as defined in Table H.7; |
|  | is the factor of galloping instability (Table H.7); if no factor of galloping instability is known, may be used. |

NOTE The factor of galloping instability is determined by , where is the most onerous angle of attack, and and are the force coefficient for drag and lift, respectively, both normalised by the depth of the cross-section for that angle of attack. The sign convention for the angle is shown in Table H.7.

(2) It should be ensured that:

|  |  |
| --- | --- |
|  | (H.30) |

where

|  |  |
| --- | --- |
|  | is the mean wind velocity and should be taken as defined in 6.3.1(19) Formula 6.4 and calculated at the height, where galloping process is expected, likely to be the point of maximum amplitude of oscillation. |

NOTE The factor 1,25 covers uncertainties in the evaluation of and the risk of wind velocities being larger than the characteristic value.

(3) If the critical vortex shedding velocity is close to the onset wind velocity of galloping :

|  |  |
| --- | --- |
|  | (H.31) |

interaction effects between vortex shedding and galloping are likely to occur, see also Figure H.6.

Table H.7 — Factor of galloping instability

| Cross-section | | Factor of galloping instability | Cross-section | Factor of galloping instability |
| --- | --- | --- | --- | --- |
| Ein Bild, das Diagramm, technische Zeichnung, Reihe, Kreis enthält.  Automatisch generierte Beschreibung  Key  1 Ice accretion  *t* = 0,06 *b* | | 3,0 |  | 1,0 |
| Ein Bild, das Diagramm, Reihe, Entwurf, technische Zeichnung enthält.  Automatisch generierte Beschreibung | 4 |
| Ein Bild, das Reihe, Diagramm, Entwurf, parallel enthält.  Automatisch generierte Beschreibung  linear interpolation |  | 1 | Ein Bild, das Entwurf, Reihe, Diagramm, Zeichnung enthält.  Automatisch generierte Beschreibung | 0,35 |
|  | 1,3 | Ein Bild, das Reihe, Diagramm, Entwurf enthält.  Automatisch generierte Beschreibung | 1,85 |
| 1 | 1,2 | Ein Bild, das Reihe, Diagramm, Entwurf enthält.  Automatisch generierte Beschreibung | 1,4 |
| Ein Bild, das Reihe, Diagramm, Entwurf, Zeichnung enthält.  Automatisch generierte Beschreibung  linear interpolation |  | 1,5 | Ein Bild, das Reihe, Diagramm, Entwurf enthält.  Automatisch generierte Beschreibung | 2,5 |
|  | 1,4 | Ein Bild, das Reihe, Diagramm, Entwurf, Zeichnung enthält.  Automatisch generierte Beschreibung | 4,3 |
|  | 1,2 | Ein Bild, das Reihe, Diagramm, Entwurf enthält.  Automatisch generierte Beschreibung | 0,5 |
| Ein Bild, das Reihe, Diagramm enthält.  Automatisch generierte Beschreibung | Sharp corners | 1,0 |  |  |
|  | 1,5 |  |  |
|  | 1,75 |  |  |
|  | 2,0 |  |  |
| Extrapolations for the factor as function of are not allowed.  NOTE  The angle indicated defines positive values of in the NOTE to H.6.2 (1). | | | | |

* + 1. Classical galloping of coupled cylinders

(1) For coupled cylinders (Figure H.9) classical galloping can occur.

(2) The onset velocity for classical galloping of coupled cylinders, , may be estimated by Formula (H.29), where and should be taken as specified in Table H.8.

(3) The condition in Formula (H.30) should be met.

Table H.8 — Factor of galloping instability for coupled cylinders

| Coupled cylinders |  |  |
| --- | --- | --- |
| Ein Bild, das Diagramm, Reihe, Kreis, Design enthält.  Automatisch generierte Beschreibung |  |  |
| Ein Bild, das Entwurf, Zeichnung, Diagramm, Design enthält.  Automatisch generierte Beschreibung |  |  |
| Ein Bild, das Diagramm, Entwurf, Kreis, Zeichnung enthält.  Automatisch generierte Beschreibung | 0 |  |

* + 1. Interference galloping of two or more free standing cylinders

(1) Interference galloping is a self-excited oscillation which can occur if two or more cylinders are arranged close together without being connected with each other.

(2) If the angle of wind attack is in the range of the critical wind direction and if (see Figure H.10), the critical wind velocity, , may be estimated by

|  |  |
| --- | --- |
|  | (H.32) |

where

|  |  |
| --- | --- |
|  | is the generalised Scruton number and should be taken as defined in H.3.5.4(1), Formula (H.18); |
|  | is the combined stability parameter ; |
|  | is the fundamental frequency of across-wind mode. Approximations are given in I.2; |
|  | is the axial spacing between adjacent cylinders; |
|  | is the diameter of the cylinders. |

NOTE The National Annex can give additional guidance on .

Ein Bild, das Diagramm, Entwurf, technische Zeichnung, Reihe enthält.

Automatisch generierte Beschreibung

*β*k ≈ 10°

Figure H.10 — Geometric parameters for interference galloping

(3) It should be ensured that:

|  |  |
| --- | --- |
|  | (H.33) |

NOTE The factor 1,25 covers uncertainties in the evaluation of and the risk of wind velocities being larger than the characteristic value.

(4) In some cases, interference galloping can be avoided by coupling the free-standing cylinders. In that case classical galloping can occur (see H.6.3).

* 1. Divergence and flutter
     1. General

(1) Divergence and flutter are instabilities that occur for flexible plate-like structures, such as signboards or suspension-bridge decks, above a certain threshold or critical wind velocity. This is an aeroelastic response.

(2) Divergence and flutter should be avoided.

(3) The procedures given below provide a means for assessing the susceptibility of a structure in terms of simple structural criteria.

* + 1. Criteria for flutter instability of structures

(1) The reduced critical flutter wind velocity , where is the critical flutter wind velocity, is the natural frequency in still air for vibrations perpendicular to the bridge deck and is the width of the bridge deck should be taken as specified in Figure H.11 for flat plates and different levels of structural damping given by . It depends on the frequency ratio , the mass ratio and the mass moment of inertia which should be taken as specified in Formulas (H.34), (H.35) and (H.36), respectively.

|  |  |
| --- | --- |
|  | (H.34) |
|  | (H.35) |
|  | (H.36) |

where

|  |  |
| --- | --- |
|  | is the torsional frequency in still air; |
|  | is the effective mass per unit length and should be taken as defined in Annex I; |
|  | is the effective mass moment of inertia per unit length and should be taken as defined in Annex I. |

|  |
| --- |
|  |
| Ein Bild, das Diagramm, Reihe, Text, Entwurf enthält.  Automatisch generierte Beschreibung |
|  |
| Ein Bild, das Diagramm, Reihe, Text, Entwurf enthält.  Automatisch generierte Beschreibung |

Key

|  |  |
| --- | --- |
| 1 | γm = 10, γI = 2 |
| 2 | γm = 30, γI = 2 |
| 3 | γm = 10, γI = 6 |
| 4 | γm = 30, γI = 6 |
|  | Reduced critical velocity |
| *n*α/*n*z | Frequency ratio |
| Interpolation between curves are not allowed | |

Figure H.11 — Reduced critical flutter wind velocity as a function of frequency ratio

(2) The critical flutter wind velocity of bridge decks should be taken as specified by Figure H.11 and using the reduction factor specified in Table H.9.

Table H.9 — Reduction factor between the critical flutter wind velocity of actual bridge decks and the critical flutter wind velocity of a flat plate with the same mass, natural frequencies and damping ratios. The flutter vibrations are assumed to be a coupling of two vibrational modes

| Bridge deck section | |  |
| --- | --- | --- |
| Flat plate | Ein Bild, das Schwarz, Dunkelheit enthält.  Automatisch generierte Beschreibung |  |
| Streamlined box-girder section | Ein Bild, das Reihe, Diagramm, Entwurf, Design enthält.  Automatisch generierte Beschreibung | Approximately 0,8–0,9 |
| Non-streamlined box-girder section | Ein Bild, das Screenshot, Rechteck, weiß, Quadrat enthält.  Automatisch generierte Beschreibung | Approximately 0,4–0,6 |
| Truss-stiffened girder | Ein Bild, das Reihe, Rechteck, parallel, Screenshot enthält.  Automatisch generierte Beschreibung | Approximately 0,6–0,8 |

(3) If all the following criteria are met, the structure can be prone to either divergence or flutter.

* The structure, or a substantial part of it, has an elongated cross-section (like a flat plate) with less than 0,25 (see Figure H.12).
* The torsional axis is parallel to the plane of the plate and normal to the wind direction, and the centre of torsion is at least leeward of the windward edge of the plate, where is the in-wind depth of the plate measured normal to the torsional axis. This includes the common cases of centrally supported signboard or canopy, and torsional centre at leeward edge, i.e. cantilevered canopy.
* The lowest natural frequency corresponds to a torsional mode, or else the lowest torsional natural frequency is less than 2 times the lowest natural frequency for vibrations perpendicular to the bridge deck.

(4) It should be ensured that:

|  |  |
| --- | --- |
|  | (H.37) |

NOTE The factor 2 covers uncertainties in the evaluation of .

* + 1. Criteria for divergent velocity of structures

(1) The critical wind velocity for divergence should be taken as specified in Formula (H.38):

|  |  |
| --- | --- |
|  | (H.38) |

where

|  |  |  |
| --- | --- | --- |
|  | is the torsional stiffness [] and should be taken as specified in I.4(8) and I.4(9); | |
|  | is the aerodynamic moment coefficient and should be taken as specified in Formula (H.39): | |
|  | | (H.39) |
|  | is the rate of change of aerodynamic moment coefficient with respect to rotation about the torsional centre, is expressed in radians; | |
|  | is the aerodynamic moment of a unit length of the structure; | |
|  | is the density of air and should be taken as specified in 6.5; | |
|  | is the in wind depth (chord) of the structure and should be taken as specified in Figure H.12; | |
|  | is the width and should be taken as defined in Figure H.12. | |

(2) Values of measured about the geometric centre of various rectangular sections are given in Figure H.12.

(3) It should be ensured that:

|  |  |
| --- | --- |
|  | (H.40) |

where

|  |  |
| --- | --- |
|  | is the mean wind velocity and should be taken as defined in Formula (6.4) at height which should be taken as defined in Figure H.1. |

NOTE The factor 2 covers uncertainties in the evaluation of and the risk of wind velocities being larger than the characteristic value.



Figure H.12 — Rate of change of aerodynamic moment coefficient with respect to geometric centre “GC” for rectangular section

1. (informative)  
     
   Dynamic characteristics of structures with linear elastic behaviour
   1. Use of this annex

(1) This Normative Annex contains guidance to determine the dynamic characteristics of linear structures. This is supplementary to Clauses 8, 9 and 10, dealing with dynamic response of structures to wind actions.

NOTE National choice on the application of this Informative Annex is given in the National Annex. If the National Annex contains no information on the application of this Informative Annex, it can be used.

* 1. Scope and field of application

(1) This Informative Annex covers modal parameters of structures with linear elastic behaviour: natural frequencies, mode shapes, equivalent masses and logarithmic decrement of damping.

* 1. General

(1) Calculation procedures recommended in this clause assume that structures possess linear elastic behaviour and classical normal modes. Dynamic structural properties are therefore characterised by:

* natural frequencies
* mode shapes
* equivalent masses
* logarithmic decrements of damping.

(2) Natural frequencies, mode shapes, equivalent masses and logarithmic decrements of damping should be evaluated, theoretically or experimentally, by applying the methods of structural dynamics.

(3) Fundamental dynamic properties may be evaluated in approximate terms, using simplified analytical, semi-empirical or empirical equations, provided they are adequately proved: Some of these equations are given in I.3 to I.5. They are appropriate for preliminary design and for checking frequencies and mode shapes given by finite element analysis.

(4) Consistent units shall be used for dynamic calculations (e.g. a force of one Newton accelerates a mass of one kilogram at 1m/s2).

(5) Care should be taken to ensure the distribution of mass in a discretised finite element model gives the correct mass moment of inertia for calculation of torsional vibration modes.

NOTE For some structures (e.g. a tall building), the mass per unit length can have contributions from imposed load.

* 1. Fundamental frequency

(1) The fundamental flexural frequency of multi-storey buildings with a height larger than 50 m should be taken as specified in Formula (I.1):

|  |  |
| --- | --- |
|  | (I.1) |

where

|  |  |
| --- | --- |
|  | is the height of the structure in m. |

Formula (I.1) gives approximate values for steel lattice towers.

(2) The frequency of the first torsional mode for reinforced concrete, composite and steel buildings may be estimated by Formula (I.2):

|  |  |
| --- | --- |
| [Hz] | (I.2) |

(3) For cantilevers with one mass at the end a simplified expression to calculate the fundamental flexural frequency *n*1 of structures may be used Formula (I.3):

|  |  |
| --- | --- |
|  | (I.3) |

where

|  |  |
| --- | --- |
|  | is the maximum displacement due to self-weight applied in the vibration direction in m. |

(4) As an alternative to Formula (I.3), for the cases in which stiffness and mass are uniformly distributed, Formula (I.4) may be used, not requiring the calculation of :

|  |  |
| --- | --- |
|  | (I.4) |

where

|  |  |
| --- | --- |
|  | is the height of the structure; |
|  | is the modulus of elasticity of the material; |
|  | is the moment of inertia of the cross-section of the cantilever; |
|  | is the equivalent mass, approximately equal to , where is the concentrated mass and is the mass per unit length of the cantilever. |

(5) The frequency for uniform horizontal façade elements and roof beam elements, may be approximated by , where is the gravity and is the maximum deflection from self-weight acting perpendicularly to the elements.

(6) The fundamental, second and third flexural frequencies, , and of a cantilever with uniform mass and stiffness should be taken as specified in Formula (I.5):

|  |  |
| --- | --- |
|  | (I.5) |

where

|  |  |
| --- | --- |
|  | is Young's modulus in [N/m2]; |
|  | is the second moment of area of the cross-section in m4; |
|  | is the mass per unit length in [kg/m]. |

Table I.1 — Values of factor,

| Mode |  | Nodal position/ | | |
| --- | --- | --- | --- | --- |
| 1 | 3,52 | 0,0 | – | – |
| 2 | 22 | 0,0 | 0,783 | – |
| 3 | 61,7 | 0,0 | 0,504 | 0,868 |

These mode shapes are illustrated in Figure I.1:



Key

|  |  |
| --- | --- |
| X | normalised Modal Displacement |
| 1 | mode 1 |
| 2 | mode 2 |
| 3 | mode 3 |

Figure I.1 — First three flexural mode shapes for a cantilever with uniform mass and bending stiffness

(7) The fundamental flexural frequency , of chimneys may be estimated by Formula (I.6):

|  |  |
| --- | --- |
|  | (I.6) |

with

|  |  |
| --- | --- |
|  | (I.7) |

where

|  |  |
| --- | --- |
|  | is the top diameter of the chimney [m]; |
|  | is the effective height of the chimney [m], and which should be taken as specified in Figure I.2; |
|  | is the weight of structural parts contributing to the stiffness of the chimney; |
|  | is the total weight of the chimney; |
|  | is equal to 1 000 for steel chimneys, and 700 for concrete and masonry chimneys. |

Ein Bild, das Diagramm, technische Zeichnung, Plan enthält.

Automatisch generierte Beschreibung

NOTE , see I.4 (2).

Figure I.2 — Geometric parameters for chimneys

(8) The fundamental ovalling frequency of a long cylindrical shell without stiffening rings may be calculated using Formula (I.8).

|  |  |
| --- | --- |
|  | (I.8) |

where

|  |  |
| --- | --- |
|  | is Young's modulus in [N/m2]; |
|  | is the shell thickness in [m]; |
|  | is Poisson ratio; |
|  | is the density of the shell material in [kg/m3]; |
|  | is the diameter of the shell in [m]. |

NOTE Formula (I.8) gives the lowest natural frequency of the shell. Stiffness rings increase .

(9) The fundamental ovalling mode shape is illustrated in Figure I.3:

Ein Bild, das Entwurf, Kreis, Zeichnung, Diagramm enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | circular cross-section |
| 2 | ovaling mode shape |

Figure I.3 — Illustration of fundamental ovalling mode shape

(10) The fundamental vertical bending frequency of a plate girder or box girder bridge may be approximately derived from Formula (I.9).

|  |  |
| --- | --- |
|  | (I.9) |

where

|  |  |
| --- | --- |
|  | is the length of the main span in m; |
|  | is Young's Modulus in N/m2; |
|  | is the second moment of area of cross-section for vertical bending at mid-span in m4; |
|  | is the mass per unit length of the entire cross-section at mid-span (for dead and super-imposed dead loads) in kg/m; |
|  | is a dimensionless factor depending on span arrangement defined below. |

|  |  |
| --- | --- |
| Plate Girder Bridge | Box Girder Bridge |
| Ein Bild, das Screenshot, Rechteck, Reihe, parallel enthält.  Automatisch generierte Beschreibung | Ein Bild, das Entwurf, Screenshot, Diagramm, Reihe enthält.  Automatisch generierte Beschreibung |

Figure I.4 — Illustration of Plate Girder and Box Girder Bridges

a) For single span bridges:

|  |  |
| --- | --- |
| if simply supported, or | Ein Bild, das Entwurf, Reihe, Rechteck, weiß enthält.  Automatisch generierte Beschreibung |
| if a propped cantilever, or | Ein Bild, das Reihe, Design enthält.  Automatisch generierte Beschreibung |
| if fixed end supports | Ein Bild, das Reihe, Rechteck, Screenshot, weiß enthält.  Automatisch generierte Beschreibung |

b) For two-span continuous bridges:

|  |  |
| --- | --- |
|  | may be obtained from Figure I.5, using the curve for two-span bridges, where |
|  | is the length of the side span and |

c) For three-span continuous bridges:

|  |  |
| --- | --- |
|  | may be obtained from Figure I.5, using the appropriate curve for three-span bridges, where |
|  | is the length of the longest side span |
|  | is the length of the other side span and |

This also applies to three-span bridges with a cantilevered/suspended main span.

If then may be obtained from the curve for two span bridges, neglecting the shortest side span and treating the largest side span as the main span of an equivalent two-span bridge.

d) For symmetrical four-span continuous bridges (i.e. bridges symmetrical about the central support):

|  |  |
| --- | --- |
|  | may be obtained from the curve for two-span bridges in Figure I.5 treating each half of the bridge as an equivalent two-span bridge. |

e) For unsymmetrical four-span continuous bridges and continuous bridges with more than four spans:

|  |  |
| --- | --- |
|  | may be obtained from Figure I.5 using the appropriate curve for three-span bridges, choosing the main span as the greatest internal span. |

If the value of at the support exceeds twice the value at mid-span or is less than 80 % of the mid-span value, then the Formula (I.9) should not be used unless very approximate values are sufficient.

(11) The fundamental torsional frequency of plate girder bridges is equal to the fundamental bending frequency calculated from Formula (I.9), provided the average longitudinal bending inertia per unit width is not less than 100 times the average transverse bending inertia per unit length.

(12) The fundamental torsional frequency of a box girder bridge may be approximately derived from Formula (I.10):

|  |  |
| --- | --- |
| [Hz] | (I.10) |

with

|  |  |
| --- | --- |
|  | (I.11) |
|  | (I.12) |
|  | (I.13) |

where

|  |  |
| --- | --- |
|  | is the fundamental bending frequency in Hz; |
|  | is the total width of the bridge; |
|  | is the mass per unit length and should be taken as defined in I.6 (4); |
|  | is Poisson´s ratio of girder material; |
|  | is the distance of individual box centre-line from centre-line of bridge; |
|  | is the second moment of mass per unit length of the individual box for vertical bending at mid-span, including an associated effective width of deck; |
|  | is the second moment of mass per unit length of cross-section at mid-span and should be taken as specified in Formula (I.14). |

|  |  |
| --- | --- |
|  | (I.14) |

where

|  |  |
| --- | --- |
|  | is the mass per unit length of the deck only, at mid-span; |
|  | is the mass moment of inertia of the individual box at mid-span; |
|  | is the mass per unit length of the individual box only, at mid-span, without associated portion of deck; |
|  | is the torsion constant of the individual box at mid-span and should be taken as specified in Formula (I.15). |

|  |  |
| --- | --- |
|  | (I.15) |

where

|  |  |
| --- | --- |
|  | is the enclosed cell area at mid-span; |
|  | is the integral around box perimeter of the ratio length/thickness for each portion of box wall at mid-span. |

NOTE Slight loss of accuracy can occur if the proposed Formula (I.15) is applied to multi-box bridges whose plan aspect ratio (= span/width) exceeds 6.



Key

|  |  |
| --- | --- |
| 1 | three-span bridges |
| 2 | two-span bridges |

Figure I.5 — Factor used for the derivation of fundamental bending frequency

* 1. Fundamental mode shape

(1) The fundamental flexural mode of buildings, towers and chimneys cantilevered from the ground may be estimated using Formula (I.16), see Figure I.6.

|  |  |
| --- | --- |
|  | (I.16) |

where

|  |  |
| --- | --- |
|  | for slender frame structures with non-load-sharing walls or cladding; |
|  | for buildings with a central core plus peripheral columns or larger columns plus shear bracings; |
|  | for slender cantilever buildings and buildings supported by central reinforced concrete cores; |
|  | for towers and chimneys; |
|  | for lattice steel towers. |

Ein Bild, das Diagramm, Reihe enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | = 2,5 |
| 2 | = 2 |
| 3 | = 1,5 |
| 4 | = 1 |
| 5 | = 0,6 |
| *ϕ*1(*z*) | normalised Modal Displacement |

Figure I.6 — Fundamental flexural mode shape for buildings, towers and chimneys cantilevered from the ground

(2) The second mode shape of cantilevered structures, e.g. towers and chimneys, may be approximated from Formula (I.17) (Figure I.7):

|  |  |
| --- | --- |
|  | (I.17) |

where

|  |  |
| --- | --- |
|  | is the vertical coordinate; |
|  | is the total height of the structure. |

NOTE Formula (I.17) derives from data gathered from a large number of existing metal chimneys with a fundamental oscillation mode characterised by Formula (I.16), with in the range of 1,6 to 2,2. The shape described by Formula (I.17) has maximum displacement at the tip of the structure (Figure I.7).



Figure I.7 — Second mode shape of towers and chimneys

(3) The fundamental flexural vertical mode of bridges may be estimated as shown in Table I.2.

Table I.2 — Fundamental flexural vertical mode shape for simply supported and clamped structures and structural elements

| Scheme | Mode shape |  |
| --- | --- | --- |
| Ein Bild, das Diagramm, Reihe, Entwurf, Design enthält.  Automatisch generierte Beschreibung | Ein Bild, das Reihe, Entwurf, Diagramm, Kleiderbügel enthält.  Automatisch generierte Beschreibung |  |
| Ein Bild, das Reihe, Diagramm, Entwurf, Design enthält.  Automatisch generierte Beschreibung | Ein Bild, das Reihe, Diagramm, Entwurf, Kleiderbügel enthält.  Automatisch generierte Beschreibung |  |

* 1. Equivalent mass

(1) The equivalent mass per unit length in mode for a line like structure should be taken as specified on Formula (I.18), where s is the linear dimension of the structure and can be horizontal, vertical or inclined.

|  |  |
| --- | --- |
|  | (I.18) |

where

|  |  |
| --- | --- |
|  | is the mass per unit length; |
|  | is the length of the structure or the structural element; |
|  | is either the portion of the structure exposed to the wind, or the portion of the structure from which vortices are shed at a given natural frequency of a corresponding mode of vibration. |

(2) The equivalent mass moment of inertia, in mode for a line like structure should be taken as specified in Formula (I.19), where s is the linear dimension of the structure and can be vertical, horizontal or inclined.

|  |  |
| --- | --- |
|  | (I.19) |

where

|  |  |
| --- | --- |
|  | is the mass moment of inertia per unit length; |
|  | is the length of the structure or the structural element; |
|  | is the mode shape of mode (predominantly in torsion); |
|  | is either the portion of the structure exposed to the wind, or the portion of the structure from which vortices are shed at a given natural frequency of a corresponding mode of vibration. |

(3) For cantilevered structures with a varying mass distribution, may be approximated by the average value of over the upper third of the structure (see Figure I.2).

(4) For structures supported at both ends of span with a varying distribution of the mass per unit length, may be approximated by the average value of over a length of centred at the point in the structure in which is maximum (see Table I.2).

* 1. Logarithmic decrement of damping

(1) The logarithmic decrement of damping for flexural vibration mode may be estimated by Formula (I.20).

|  |  |
| --- | --- |
|  | (I.20) |

where

|  |  |
| --- | --- |
|  | is the logarithmic decrement of structural damping; |
|  | is the logarithmic decrement of aerodynamic damping for the flexural vibration mode; |
|  | is the logarithmic decrement of damping due to special devices (tuned mass dampers, sloshing tanks etc.) taking into account the modal displacement at their location. |

Care should be taken to ensure it is appropriate to add all three contributions to damping for the limit state under consideration. For example, should not be included when calculating responses due to vortex shedding. Similarly, damping devices are usually configured to work at a serviceability limit state and may be ineffective at the ultimate limit state.

Approximate values of logarithmic decrement of structural damping , may be taken from Table I.3. Values of structural damping are often mode, amplitude and frequency dependent, and damping can be reduced with increasing slenderness. Values will depend on factors such as whether or not the structure remains within the linear elastic range, whether slip occurs in joints, or only material hysteresis occurs. The type of foundation and ground may also have a significant influence. Where the design of a structure is critically dependent on the value of structural damping, this should be investigated in design and verified by testing. Provision for damping devices should also be incorporated in the design, if measured values need to be supplemented.

(2) The logarithmic decrement of aerodynamic damping , for along-wind vibrations may be calculated for flexural mode from Formula (I.21).

|  |  |
| --- | --- |
|  | (I.21) |

where

|  |  |
| --- | --- |
|  | is the density of air; |
|  | is the force coefficient for wind action in the wind direction; |
|  | is the width of the structure (refer to Figure 10.1); for horizontal structures, use and should be taken as defined in Figure 10.1; |
|  | is the generalised mass, of mode , and should be taken as defined in I.4; |

and the integral is calculated over the length of structure exposed to the wind ().

Alternatively, for structures with uniform properties along the span, may be estimated for the fundamental flexural mode from Formula (I.22).

|  |  |
| --- | --- |
|  | (I.22) |

(3) The logarithmic decrement of aerodynamic damping , for across-wind dynamic response for slender structures in H.2 may be calculated for flexural mode from Formula (I.23).

|  |  |
| --- | --- |
|  | (I.23) |

where

|  |  |
| --- | --- |
|  | is the force coefficient for wind action in the across-wind direction; |

NOTE The aerodynamic damping for vortex-induced vibrations of slender structures is specified in Annex H.

(4) If special dissipative devices are added to the structure, should be calculated by suitable theoretical or experimental techniques. Their design should also include for differences between calculated and measured dynamic characteristics.

Table I.3 — Approximate values of logarithmic decrement of structural damping in the fundamental mode,

| **Structural type** | | | **Structural damping,** |
| --- | --- | --- | --- |
| reinforced concrete buildings | | | 0,10 |
| steel buildings | | | 0,05 |
| mixed structures concrete + steel | | | 0,08 |
| reinforced concrete towers and chimneys | | | 0,03 |
| unlined welded steel stacks without external thermal insulation | | | 0,012 |
| unlined welded steel stack with external thermal insulation | | | 0,020 |
| steel stack with one liner with external thermal insulationa | |  | 0,020 |
|  | 0,040 |
|  | 0,014 |
| steel stack with two or more liners with external thermal insulationa | |  | 0,020 |
|  | 0,040 |
|  | 0,025 |
| steel stack with internal brick liner | | | 0,070 |
| steel stack with internal gunite | | | 0,030 |
| coupled stacks without liner | | | 0,015 |
| guyed steel stack without liner | | | 0,04 |
| steel bridges + lattice steel towers | Welded | | 0,02 |
| high resistance bolts | | 0,03 |
| ordinary bolts | | 0,05 |
| individual members of steel structures (high aspect ratio results in low damping) | | | 0,003 to 0,03 |
| composite bridges | | | 0,04 |
| concrete bridges | pre-stressed without cracks | | 0,04 |
| with cracks | | 0,10 |
| timber bridges | | | 0,06 to 0,12 |
| bridges, aluminium alloys | | | 0,02 |
| bridges, glass or fibre reinforced plastic | | | 0,04 to 0,08 |
| cables | parallel cables | | 0,006 |
| spiral cables | | 0,020 |
| * The values for timber and plastic composites are indicative only. In cases where aerodynamic effects are found to be significant in the design, more refined figures are needed through specialist advice (agreed if appropriate with the competent Authority). * For cable supported bridges the values given in Table I.3 need to be factored by 0,75. * The values of damping given in this table are appropriate for ultimate limit state analyses under wind actions. Damping is often amplitude dependent and so lower values may apply to serviceability and fatigue limit states. | | | | |
| a For intermediate values of *h/b*, linear interpolation may be used. | | | | |

1. (informative)  
     
   Response of steel lattice towers and guyed masts
   1. Use of this annex

(1) This Informative Annex deals with supplementary rules for wind actions on lattice towers, guyed masts and guyed chimneys, and on their response; it has been transferred from EN 1993‑3.

NOTE National choice on the application of this Informative Annex is given in the National Annex. If the National Annex contains no information on the application of this Informative Annex, it can be used.

* 1. Scope and field of application

(1) This informative Annex contains supplementary information about wind actions on towers and guyed masts as follows:

* response of lattice towers, see J.4; and
* response of guyed masts, see J.5.
  1. General
     1. Symbols

(1) In addition to symbols given in EN 1993‑1‑1, symbols given in 3.2 have been used in this Annex.

* 1. Response of lattice towers
     1. Criteria for static methods

(1) The equivalent static method (see J.4.2) should usually be used if the criteria in J.4.1(3) are met. If not, more complex methods such as the spectral analysis method, see J.4.3, should be used. Specialist advice is necessary.

(2) The equivalent static method includes an allowance for the dynamic amplification of response due to gust buffeting that is typical of most towers likely to be constructed in accordance with this standard. The check for applicability of the static procedure according to Formula (6.3) should be considered for guidance only. Dynamic augmentation generally increases in successively higher panels of any tower, particularly when supporting large concentrations of ancillary items or when using a concave outline profile (Eiffelization). In such cases, caution should be exercised in applying the static procedure to towers where these effects are considerably more than those typically encountered.

(3) The equivalent static procedures may be used if:

|  |  |
| --- | --- |
|  | (J.1) |

where

|  |  |
| --- | --- |
|  | is the sum of the panel wind resistances (including ancillaries), commencing from the top of the tower, such that is just less than one-third of the overall summation for the whole tower (in m2), see E.5.3.2; |
|  | is the density of the material of the tower structure [kg/m3]; |
|  | is the total mass of the panels making up [kg]; |
|  | is the height of the tower [m]; |
|  | is the total height of the panels making up ,­ but not greater than [m]; |
|  | is a volume/resistance constant taken as 0,001 m; |
|  | is the depth in the direction of the wind, equal to: |
|  | * base *d* for rectangular towers [m]; |
|  | * 0,75 × base width for triangular towers [m]. |

* + 1. Equivalent static method
       1. General

(1) For symmetrical towers constructed of leg members with triangulated bracings, with or without ancillaries for which the wind resistance has been calculated using Annex E, maximum member forces should be derived in accordance with J.4.2.1 to J.4.2.5. For towers with complex attachments, the maximum member forces should be determined in accordance with J.4.2.8.

For symmetric triangular and square towers, the wind loads in the cross-wind direction will not govern design and may thus be ignored. For un-symmetric towers these loads are taken into consideration.

* + - 1. Wind loading

(1) The wind force in the direction of the wind on the tower should be determined with Clause 7, but using the wind force coefficients given in Annex E.

(2) The tower shall be analysed under the effect of mean-wind load; individual peak member load-effects shall be obtained by factoring mean-wind load effects to account for gust-wind loading and the member's position in the tower.

(3) The mean wind load in the direction of the wind on the tower should be taken as:

|  |  |
| --- | --- |
|  | (J.2) |

* + - 1. Load effects — Tower leg members

(1) The total force in a tower leg member due to mean-wind and along-wind gust buffeting should be determined from:

|  |  |
| --- | --- |
|  | (J.3) |

where

|  |  |
| --- | --- |
|  | is the force in the tower leg member at height due to mean-wind load, ; |
|  | is the size factor from Annex F; it shall be calculated for length () and effective height ; |
|  | is the dynamic factor from Annex F; |
|  | is the structural factor equal to ; |
|  | is the height above the tower base at which the load effect is required; |
|  | is the overall tower height. |

(2) The dynamic factor, may be taken as 1,10 for towers that comply with the criteria of J.4.1.

NOTE For steel lattice towers, the cross-sectional background response factor taking into account the lack of correlation of pressure acting on a cross-section, when calculating the size factor, .

(3) The factor accounts for the increase of dynamic augmentation with height. Therefore, the provisions of F.7(3) shall not be applied when determining .

* + - 1. Load effects — Tower foundations

(1) The maximum load-effect , on a tower’s foundations should be determined from:

|  |  |
| --- | --- |
|  | (J.4) |

where is the load-effect on the tower's foundations determined from the mean wind load .

* + - 1. Load effects — Tower bracing members

(1) The gust-wind factors used to calculate bracing member forces should be based on the configuration of the tower.

NOTE Shear forces on foundations are determined from J.4.2.4.

(2) For towers in which the leg slopes are such that, when projected, they intersect above the top of the tower (see Figure J.1(a)) the maximum bracing force, or shear above a given level should be determined from J.4.2.3.

NOTE Forces in bracing members at leg slope changes can have significant components from the leg force and from the shear.

(3) For towers in which the legs in the panel being considered are inclined such that, when projected, they intersect below the height of the tower (see Figure J.1(b)), two 'patch' cases should be considered:

1. the sum of the load-effects due to mean-wind loading between the intersection and , and mean-wind plus gust-wind above the intersection. The size factor, shall be calculated for the length of the patch above the intersectionn point subject to mean and gust wind; its effective height, shall be equal to the intersection point height plus 0,6 of the length of the patch.
2. the sum of the load-effects due to mean-wind loading above the intersection and mean-wind plus gust-wind below the intersection. The size factor, shall be calculated for the length of the patch between the intersection point and subject to mean and gust wind; its effective height, shall be equal to plus 0,6 of the length of the patch.

(4) For more than one such intersection, two patch loading cases should be analysed for each panel, see Figure J.1(c).

For bracing members above the highest intersection point the procedure of J.4.2.3 may be used.

|  |  |  |
| --- | --- | --- |
| Ein Bild, das Entwurf, Diagramm, Zeichnung, Reihe enthält.  Automatisch generierte Beschreibung | | |
| **a) Case 1** | All shears determined from mean loading and gust response factor | |
| Ein Bild, das Diagramm, Reihe, Entwurf, Plan enthält.  Automatisch generierte Beschreibung | | |
| **b) Case 2** | Patch loading for panel “A” | |
| Ein Bild, das Diagramm, technische Zeichnung, Entwurf, Plan enthält.  Automatisch generierte Beschreibung | | |
| **c) Case 3** | Patch loading for panel “A”:  patch 1  patch 2 | Patch loading for panel “B”:  patch 1  patch 2 |

Key

|  |  |
| --- | --- |
| 1 | panel “A” |
| 2 | projection of legs from panel “A” |
| 3 | mean |
| 4 | panel “A” as case 1, treat panels above |
| 5 | “gust” |
| 6 | panel “B” |
| 7 | panel “B” as case 1, treat panels above |

Figure J.1 — Shear patch loading

* + - 1. Loading on cables and guys supported by the tower

(1) The maximum wind load applied to a tower in the direction of the wind due to wind action on an attached cable, :

|  |  |
| --- | --- |
|  | (J.5) |

where

|  |  |
| --- | --- |
|  | is the mean wind pressure at the effective height of the cable, metres above site ground level determined in accordance with Clause 6; |
|  | is the wind resistance of the cable, normal to the cable in the plane containing the cable and the wind, determined in accordance with E.3.8; |

NOTE 1 There will also be a wind load applied to the tower perpendicular to the wind direction in a horizontal plane equal to .

NOTE 2 When calculating , can be taken as unity.

* + - 1. Loading for calculating deflections and rotations

(1) Deflections and rotations are normally only important to satisfy serviceability requirements. The serviceability criteria should be defined by the client in the project specification.

* + - 1. Wind loading for towers with complex attachments

(1) For towers that contain unsymmetrically placed large ancillaries and/or cables imposing significant torsional and crosswind loads, the total forces due to the effect of wind load should allow for the combined action of wind on individual parts, both along wind and crosswind, when appropriate.

(2) The fluctuating load effects caused by cross wind turbulence should be considered in conjunction with along wind load effects.

(3) To determine the total load effects in such cases, the mean along wind load effect should be separated from the fluctuating wind load effect. Thus, the tower should be analysed under the mean wind load in the direction of the wind () as determined from J.4.2.1(1).

If cables are present the mean load on the cables should be used. see J4.2.6.

(4) The individual load effects should then be calculated as:

1. the mean wind load effect, , determined from the mean wind load .
2. the fluctuating in line wind effect, , determined from:

|  |  |
| --- | --- |
|  | (J.6) |

1. Turbulence in the crosswind direction causes fluctuating crosswind load effects () which, in the absence of other information should be taken as:

|  |  |
| --- | --- |
|  | (J.7) |

where

|  |  |
| --- | --- |
|  | is a factor to allow for crosswind intensity of turbulence; |
|  | is the crosswind lift coefficient of the structure (and any ancillaries if present) over the panel height concerned multiplied by the reference area when viewed in the crosswind direction. Refer to E.3.4 for definition of . |

NOTE 1 The value *K*X is 1,0 unless the National Annex gives a different value.

NOTE 2 Crosswind turbulence will cause fluctuating crosswind loads even in symmetric towers; however, such loads will not normally affect the critically loaded elements except for fatigue.

(5) The total load effect in any member due to wind should then be taken as:

|  |  |
| --- | --- |
|  | (J.8) |

where

|  |  |
| --- | --- |
|  | is the load effect in the member due to the mean wind loads, on all attached cables. |
|  | is load effect in the member due to the leeward fluctuating wind loads on all attached cables. |

* + 1. Spectral analysis method

(1) When response to along-wind forces is calculated by a spectral analysis, the meteorological conditions to be assumed should be those defined in 6, and the wind force coefficients taken as those given in Annex E. In addition, the parameters defined in Annex F should be adopted in the absence of more accurate information.

NOTEThe National Annex can give further information.

(2) Cross wind turbulence will cause fluctuating load effects which need to be considered in conjunction with in-line wind loads. Appropriate parameters, consistent with those adopted for leeward effects should be adopted.

NOTE The National Annex can give further information.

* + 1. Crosswind vortex vibrations

(1) If towers support large prismatic, cylindrical or bluff bodies or may be expected to become heavily blocked by icing, their susceptibility to vortex-excited vibrations and/or galloping should be determined, in accordance with Annex H.

* 1. Response of guyed masts
     1. General

(1) The maximum forces to be used in the design of mast components and foundations should be calculated with due allowance for the response to wind turbulence.

(2) Such forces should represent the resultant effect of an equivalent static loading due to wind speeds equal to the appropriate 10 minute mean value, acting only in the wind direction, and fluctuating loading both leeward and, where relevant, crosswind due to gustiness.

* + 1. Criteria for static methods

(1) Generally, static analysis procedures may be used to determine the maximum forces in the members of a mast, see J.5.3. Only for masts which may be prone to significant dynamic response is it necessary to undertake dynamic response methods, see J.5.4.

(2) The design of major masts whose economic consequences of failure or potential hazards resulting from failure are high (see EN 1990) should be checked by dynamic response procedures if required by the project specification.

(3) The following criteria should be satisfied for the static analytical procedures to be used:

1. any cantilever has a total length above the top guy level of less than half the spacing between the penultimate and top guys;
2. the parameter is less than 1, where

|  |  |
| --- | --- |
|  | (J.9) |

with

|  |  |
| --- | --- |
|  | (J.10) |

where

|  |  |
| --- | --- |
|  | is the number of guy levels; |
|  | is the cross sectional area of guy at level ; |
|  | is the elastic axial modulus for guy at level ; |
|  | is the length of guy at level ; |
|  | is the no. of guys attached at level ; |
|  | is the height above the mast base of the th guy level; |
|  | is the slope of the guy chord at level to the horizontal; |
|  | is the elastic modulus for the mast; |
|  | is the average mast column bending inertia; |
|  | is the average span between guy levels. |

1. The parameter is less than 1, where

|  |  |
| --- | --- |
|  | (J.11) |

where

|  |  |
| --- | --- |
|  | is the average mass per unit length of the mast column including ancillaries [kg/m]; |
|  | is the average face width of the mast [m]; |
|  | is the mean wind speed at top of mast [m/s]; |
|  | is the average total wind resistance of the mast column and ancillaries obtained from Annex E [m2/m]; |
|  | is the height of mast, including cantilever if present [m]. |

(4) If any of the criteria in (3) are not satisfied, then the spectral analysis method (see J.3.4) should be followed.

If the stiffness ratio ([ of the cantilever]/[ of the mast span immediately below the cantilever]) is less than 0,5 then the patch loading procedure not necessarily reflects the dynamic response of the cantilever adequately. Thus care should be exercised and alternative methods considered, such as the spectral analysis procedure given in Clause J.5.4. These considerations can also be appropriate where there is a large variation of EI over the height of the cantilever.

For the assessment of existing structures where the cantilever is not being altered, the patch loading procedure may be used with the agreement of the designer, the client and the competent authority, provided the cantilever has been monitored and there is no evidence of unacceptable performance.

* + 1. Equivalent static methods
       1. General

(1) To allow for the dynamic response of masts to wind loading the mast should be analysed for a series of static ‘patch’ loading patterns based on the mean loading augmented by wind load ‘patches’. This procedure requires several static wind analyses for each wind direction considered, the results being combined to provide the maximum response.

(2) For masts of symmetrical structural cross-section with triangulated bracing, either without ancillaries or with ancillaries symmetric in the wind direction being considered and are not likely to be dynamic sensitive (see J.5.2), the maximum forces should be derived in accordance with J.5.3.2.

(3) For masts containing ancillaries which are un-symmetric in the wind direction being considered, the additional forces due to cross wind effects should be determined in accordance with J.5.3.2.8.

* + - 1. Load cases to be considered
         1. Mean wind loading

(1) The wind load in the direction of the wind on the mast column due to the mean wind should be taken as:

|  |  |
| --- | --- |
|  | (J.12) |

where

|  |  |
| --- | --- |
|  | is the wind resistance of the mast column (and any ancillaries if present) in the direction of the wind over the mast section concerned, at a height metres above the site ground level, determined in accordance with E.5. |

(2) The loads should be taken as acting at the level of the centre of areas of faces, including ancillaries if present within the section height.

(3) The wind loading on the guys, , normal to the guys in the plane containing the guy and the wind, due to the mean wind should be taken as:

|  |  |
| --- | --- |
|  | (J.13) |

where

|  |  |
| --- | --- |
|  | is the wind resistance of the guy under consideration determined in accordance with E.5.8. |

(4) If a uniform loading is applied to the guys then should be taken as the wind speed at the height of the relevant guy attachment to the mast.

(5) The load effects due to the mean wind should be determined for each component of the mast by a geometric non-linear static analysis under the mean loading and .

* + - * 1. Patch loads

(1) In addition to the mean loading derived from J.5.3.2.1 successive patch loads should be applied as follows:

* on each span of the mast column between adjacent guy levels (and the span between the mast base and the first stay level);
* over the cantilever if relevant;
* from midpoint to mid point of adjacent 'spans';
* from the base to the mid height of the first guy level;
* from the mid height of the span between the penultimate and top guy if no cantilever is present, but to include the cantilever if relevant.

(2) These are shown in Figure J.2. The ‘patch’ load should be taken as:

|  |  |
| --- | --- |
|  | (J.14) |

where

|  |  |
| --- | --- |
|  | should be taken as defined in J.5.3.2.1; |
|  | is a scaling factor; |
|  | is the turbulence intensity as given in 6.4, depending on the site terrain and the orography. |

NOTE 1 The scaling factor accounts for the multi-modal dynamic response of guyed masts to gust buffeting.

NOTE 2 The value *k*s is 3,5 unless the National Annex gives a different value.

For simplicity uniform patch loads may be used taking as the height at the top of the patch for and .

Ein Bild, das Diagramm, Text, Reihe, Plan enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | mean wind loading |
| 2 | patch loads |

Figure J.2 — Application of patch loads

(3) These patch loads should be applied to the mast, under mean wind loading determined from J.5.3.2.1.

(4) For masts up to 50 m height only one case needs to be considered, with the mean and patch load enveloping the mast. For this, the scaling factor () should be taken as 3,5.

In such cases the shear bracing in each span should be designed for the maximum shear (and associated torsion) in that span.

In such cases the legs and their connections in each span should be designed for the maximum (and minimum) leg load in that span.

In such cases if the mast supports a cantilever, then (i) mean plus 1,4 times the patch loading on the cantilever and mean load on the mast and (ii) mean load on the cantilever and mean plus patch loading on the mast should also be considered.

* + - * 1. Loading on guys

(1) For each patch loading case on the mast column, as given in J.5.3.2.2 patch wind loads, , should be applied within the same boundaries, see Figure J.3. These patch loads should be applied normal to each guy in the plane containing the guy and the wind, and taken as:

|  |  |
| --- | --- |
|  | (J.15) |

where

|  |  |
| --- | --- |
|  | is a scaling factor which includes the gust peak factor and an allowance for the dynamic response of the mast to gust buffeting; |
|  | is the wind resistance normal to the guy in the plane containing the guy and the wind determined in accordance with E.5.8. |

NOTE 1 The scaling factor accounts for the multi-modal dynamic response of guyed masts to gust buffeting.

NOTE 2 The value *k*s is 3,5 unless the National Annex gives a different value.

(2) For simplification the patch loading may be ‘smeared’ over the whole height of the guys in question by multiplying the above wind load by the ratio

where

|  |  |
| --- | --- |
|  | is the “height” of the patch on the actual guy; and |
|  | is the height to the attachment of the guy to the mast. |

Ein Bild, das Text, Diagramm, Reihe, parallel enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| a | patch loading on mast column (typical) |
| b | patch load on guys 2 and 3 (may be smeared, see J.5.3.2.3(2)) |
| c | mean load on guy 3 |

Figure J.3 — Patch loading on guys

* + - * 1. Derivation of response under patch loads

(1) The load effect in each element of the mast column and guys derived from each patch load applied successively, , should be calculated.

(2) This should be done by calculating the difference between the load effect from the patch load combined with the mean load () and the load effect of the mean load alone ().

(3) These load effects should then be combined as the root sum of squares, or:

|  |  |
| --- | --- |
|  | (J.16) |

where

|  |  |
| --- | --- |
|  | is the load effect (response) from the th load pattern; |
|  | is the total number of load patterns required; |
|  | is the total effective load effect of the patch loads. |

* + - * 1. Total load effects

(1) The total load effects for each component of the mast column, , should be determined from:

|  |  |
| --- | --- |
|  | (J.17) |

where

|  |  |
| --- | --- |
|  | is the mean load effect determined from J.5.3.2.1; |
|  | is the fluctuating load effect determined from J.5.3.2.4 using the sign to produce the most severe effect. |

(2) In the calculation of the total force in the shear bracing in each span of the mast column in accordance with (1) above, the minimum value within that span should be taken as the highest calculated at a distance of one quarter of the span from either adjacent guy attachment levels (or the mast base if relevant). In this context ‘span’ refers to the distance between adjacent guy levels or between the base and the lowest guy level, see Figure J.4.

Ein Bild, das Diagramm, Reihe, Entwurf, technische Zeichnung enthält.

Automatisch generierte Beschreibung

Key

|  |  |
| --- | --- |
| 1 | minimum value to be used in this span |
| 2 | envelope of forces in bracing members arising from patch loading (absolute values shown) |
| 3 | force in shear bracing |

Figure J.4 — Minimum forces in shear bracing in mast column

* + - * 1. Wind directions to be considered

(1) For each member of the mast, the wind direction giving the most severe total load effect should be considered. This in practice means that several wind directions should be investigated.

(2) If the mast is nearly symmetrical in geometry and loading, at least three wind directions should be analysed for a triangular mast guyed in three directions, i.e. 90°, 30° to a face and 60° to a face. For a mast with square cross-section and guyed in four directions, at least two wind directions should be analysed, normal to a face and 45° to a face (similar wind directions apply to a 4-stayed circular mast). Examples are shown in Figure J.5.

To account for overall buckling of symmetric masts (see 5.1(5)) introduction of a lateral effect (such as a cross-wind force of 2% of the along wind force or a wind direction of 2° off the notional wind direction) should be provided in undertaking the second order analysis.

Ein Bild, das Diagramm, Entwurf, Design enthält.

Automatisch generierte Beschreibung

Figure J.5 — Typical wind directions to be considered

* + - * 1. Loading for calculating deflections and rotations

(1) Deflections and rotations are normally only important to satisfy serviceability requirements. The serviceability criteria should be defined by the client in the project specification.

* + - * 1. Wind loading for masts with complex attachments

(1) For masts that contain unsymmetrically placed large ancillaries and/or cables imposing torsional and cross wind loads, the total forces due to the effects of wind load should allow for the combined action of wind on individual parts, both along wind and crosswind, when appropriate.

(2) Cross wind turbulence will cause fluctuating load effects. This may need to be considered in conjunction with along wind loads.

(3) The procedure for separating the mean along wind loads from the fluctuating loads needs to be carried out, as set out for towers in J.4.2.8. For guyed masts, however this will necessitate a series of transverse patch wind loads to be applied in a similar manner to those for along wind as set out in J.5.3.2.2.

(4) The total load effects should then be determined from:

|  |  |
| --- | --- |
|  | (J.18) |

where

|  |  |
| --- | --- |
|  | is the load effect from the in-line patch loads; |
|  | is the load effect from the cross-wind patch loads; |
|  | is a factor to allow for cross wind intensity of turbulence. |

NOTE 1 The value *K*x is 1,0 unless the National Annex gives a different value.

NOTE 2 Cross wind turbulence will cause fluctuating cross wind loads even in symmetric masts; however such loads will not affect the critically loaded elements.

(5) Alternatively, for simplification the cross wind turbulence effects need not be calculated explicitly as in J.5.3.2.8(4) above but the in-line peak load effects, , from J.5.3.2.5(1) should be increased by 10% to allow for cross wind effects.

* + 1. Spectral analysis method

(1) When response is calculated by spectral analysis this should be used for the resonance contribution to the response only.

(2) The non-resonant response may be determined using the general static procedure (See J.5.3.2) using .

(3) The meteorological conditions to be assumed should be those defined in 6, and the wind resistance taken as that given in Annex E. In addition, the parameters defined in Annex F should be adopted in the absence of more accurate information.

(4) Cross wind turbulence will cause fluctuating load effects which need to be considered in conjunction with along wind loads. Appropriate parameters, consistent with those adopted for along wind effects should be adopted.

(5) Response should be calculated for all modes of vibration having natural frequencies less than 2 Hz.

* + 1. Vortex-excited vibrations

(1) When masts support large bluff bodies or are likely to become heavily blocked by icing, then susceptibility to vortex-excited vibrations, should be taken into account in accordance with Annex H.

* + 1. Guy vibrations

(1) The mast guys should be checked for high frequency vortex-excited vibrations and guy galloping, particularly when the guys are iced, as follows:

1. *Vortex excitation*

Guys may be subject to low amplitude resonant type vibrations at low wind speeds caused by vortex excitation at high frequency.

As excitation can occur in high modes general rules cannot be set down. However as a guide, experience shows that such vibrations are likely to occur if the still air tensions in the guys are in excess of ten per cent of their breaking load.

1. *Galloping (including rain induced vibrations)*

Guys may be subject to galloping excitation when coated with ice or thick grease. The accretion of ice or grease can form aerodynamic shapes which provide lift and drag instabilities. These result in low frequency high amplitude vibrations. Similar vibrations are also known to occur under conditions of rain.

Again general rules cannot be provided as the occurrence of galloping is critically dependent on the formation of ice, or profile of grease. It will generally only occur on large diameter guys and is relatively insensitive to initial stay tensions. See Annex H.

(2) If guy vibrations are observed, dampers or spoilers should be provided as required to limit the resulting stresses, see EN 1993‑3 and EN 1993‑1‑11.

(3) Fatigue checks of the anchorages should be made if such vibrations are known to have occurred and no remedial action has been taken. In such cases specialist advice should be sought.

1. (informative)  
     
   Guidance on derivation of design parameters from wind tunnel tests and numerical simulations
   1. Use of this annex

(1) This Informative Annex provides complementary/supplementary guidance to 5.5 for specifying the design assisted by testing simulations.

NOTE National choice on the application of this Informative Annex is given in the National Annex. If the National Annex contains no information on the application of this informative annex, it can be used.

* 1. Scope and field of application

(1) This Informative Annex applies to structural design of building and civil engineering works.

(2) This Informative Annex does not apply to non-synoptic winds and thermal effects.

* 1. General

(1) Calculation of wind actions and effects on structures requires input data, which are measured in the wind tunnel and/or derived from numerical simulations. For the most common cases, such data are available in the literature and are summarised in this Eurocode Part. For less common situations, specific data must be produced in the design stage. This Annex outlines criteria that should be followed when running wind tunnel tests or computational simulations and for the extraction of input data for use in compliance with prEN 1991-1-4.

NOTE Wind tunnel tests and computational simulations can also be used for checking the results of calculations and for optimising the aerodynamic and structural performance of wind-exposed structures. This can lead to an economic advantage and/or an increase in safety.

(2) Wind tunnel tests and computational simulations should be used within their fields of applicability and complement each other if necessary. Proof should be given that the technique used (either experimental or computational) is appropriate for the problem at hand, and that the accuracy obtained is compatible with that required. In both cases, calibration of the setup (physical or computational) should be done against existing data.

(3) Design, execution, and interpretation of wind tunnel tests and computational simulations should be carried out by a specialist or specialised laboratory. This Annex aims at providing the design Engineer with basic information about the procedures of the most common wind tunnel tests and computational analyses, so to facilitate interaction with the specialist in charge of testing or simulation. This Annex also contains some minimum requirements that the design Engineer or the checking Engineer should request when outsourcing tests or simulations.

NOTE More details about experimental techniques and computational approaches can be found in the technical literature.

(4) In order to accurately reproduce the actions and effects of wind on constructions, the relevant features of the wind flow in the atmospheric boundary layer should be reproduced. In particular, for vertical structures, the mean velocity and turbulence intensity profiles should be modelled. Only in cases where the vertical variability of the wind field does not significantly affect the action (e.g. for a bridge deck), uniform (laminar or turbulent) wind conditions may be used.

(5) Wind tunnel tests and computational simulations should be designed for each specific situation and class of problem. The class of problem should be identified prior to tests and simulations by the Specialist, based on the information provided by the designer.

NOTE The class of problem depends on the characteristics of the incoming wind, on the type of structure, of its expected qualitative aerodynamic behaviour and structural response. The comprehensive general categorization of the classes of problem is out of the scope of this Annex.

(6) Statistical processing of the measured quantities should comply with Annex M.

(7) The recommended application of wind tunnel testing (WTT) and of computational wind engineering (CWE) to different classes of problem (and at different stages in the design process) should be taken from Table K.1. For most classes of problems, the results of CWE analyses should not be relied upon to give absolute values of parameters as inputs to the design of civil engineering structures.

NOTE 1 Currently a limited number of well-documented applications of CWE exist, with respect to Wind Tunnel Tests.

NOTE 2 For what concerns CWE, the prudential recommendations of Table K.1 are mainly inspired by the current level of technical transfer from scientific research to CWE consultancy. Recommendations can be subject to change with time, and procedures currently advised only for the preliminary stage of design can be extended to the detailed design once a sufficiently large number of well-documented case studies will become available.

NOTE 3 WTT and CWE can also be used to compare different solutions at the preliminary design stage, so to select the most performing one from the technical and economical points of view.

Table K.1 — Fields of applicability of WTT and CWE (A: advised, N: not advised)

| Class of problem | WTT | | CWE | |
| --- | --- | --- | --- | --- |
| Prelim. stage | Detailed Design | Prelim. stage | Detailed Design |
| Topographic effects | A | A | A | A |
| Local pressures | A | A | A | N |
| Overall forces | A | A | A | N |
| Gust buffeting response | A | A | A | N |
| Vortex shedding response | A | A | A | N |
| Galloping | A | A | A | N |
| Flutter | A | A | A | N |
| Key  **A:** advised  **N:** not advised | | | | |

* 1. Derivation of design parameters from wind tunnel tests
     1. General

(1) Wind tunnel testing is based on reproduction at a reduced scale of the physical phenomena taking place in real life. Scale reduction should apply not only to geometry, but to all the physical quantities involved in the interaction process between wind and structures. Scaling is performed with different rules depending on individual cases. Scaling rules should be applied to both structural parameters and wind flow properties.

NOTE The scale of a given physical quantity is defined as the ratio between the full-scale and the laboratory-scale values of the quantity.

* + 1. Wind tunnels and flow characteristics

(1) Boundary Layer Wind Tunnels (BLWT) should be used when assessing wind loads and their effects on civil engineering structures. Only in cases where the vertical spatial variability of the wind field is not of interest, aeronautical wind tunnels may be used. In any case, the flow features should be homogeneous in the test section.

(2) Testing should take place in turbulent flow conditions; smooth flow conditions can be considered a reference case for comparison.

NOTE In some cases smooth flow conditions provide an upper limit of the action and of the response. In other cases, it is the actual most severe condition, e.g. when evaluating the shedding-induced response at low reference wind velocities.

(3) For an accurate reproduction of physical phenomena, the flow parameters in the wind tunnel should correspond, after scaling, to those of the actual flow. This means that the following rules should be observed:

1. dimensionless parameters (for example Reynolds number, Strouhal number, turbulence intensity, etc.) in the tunnel should have the same value as at full-scale;
2. to parameters having the same physical dimensions, the same scale should be applied; this means, for example, that parameters having length dimensions (height of a building, turbulence length scale, depth of the atmospheric boundary layer, etc.) should all be scaled by the same quantity;
3. scales of quantities having different physical dimensions should meet the dimensional equations; this means that, for example, the velocity scale should be equal to the length scale divided by the time scale.

(4) In general, it is not possible to meet all the above requirements simultaneously; it is therefore common practice to use a distorted modelling, in order to fulfil only some of the scaling constraints. The selection of which scaling constraints can be violated in each situation is extremely complex and largely affects the quality of the experimental results. Experimentalists should therefore justify the choices made. In particular:

1. for vertical structures, the mean velocity and turbulence intensity profiles should reproduce full-scale conditions up to a height equal to at least 1,5 times the maximum height of the structure;
2. for all structures, the turbulence integral length scale in the tunnel should be as close as possible to the full-scale value, reduced through the geometric scale of the structural model. In modelling the turbulence spectrum in the wind tunnel, inaccuracy at the low frequencies is acceptable, whereas the high-frequency components should be properly reproduced.

(5) For an accurate reproduction of aerodynamics, Reynolds number in the wind tunnel should be the same as in full-scale. Usually this requisite cannot be met, leading to negligible errors for sharp-edged geometries but to significant errors for rounded geometries; in the latter case attention should be paid in the design of tests and in the interpretation of results.

NOTE One possibility for reducing the error associated with a lower Reynolds number in the wind tunnel is to increase the surface roughness of the model with respect to the actual value, or to trigger turbulence transition by using a localised surface disturbance (e.g. by adding roughness). Roughening the surfaces can lead to an effective value of the Reynolds number 3 or 4 times higher than the actual one.

(6) The confining effect the wind tunnel has on the flow (blockage) leads to a variation of the pressure acting on the surfaces of the models; this should be taken into account when defining the length scale. In particular, the projection of the volume occupied by the model on the cross-section plane of the tunnel (blockage ratio) should not exceed 5% of the area of the cross-section itself. For slightly larger values of the blockage ratio, in any case less than 10%, measurements are affected by small errors and can still be acceptable, provided they are properly corrected. For blockage ratios exceeding 10%, measurements are potentially unreliable. Open jet tunnels have negative blockage effects, resulting in unconservative results which should always be corrected.

NOTE In the case of complicated building surroundings the effective blockage is not easy to determine and there is no theory of 3D blockage. This is a significant issue when testing in city centre environments.

(7) The static pressure should be kept constant along the tunnel.

NOTE Variations of static pressure arising from blockage by the model and the formation of a shear layer along the floor, ceiling, and lateral walls can be compensated if the tunnel is equipped with mobile lateral walls or ceiling. These features make it possible to create a variable cross-section along the tunnel and such variability can be adjusted to obtain a uniform static pressure along the tunnel. Blockage-tolerant tunnels are a common way to accommodate blockage issues.

(8) In the tests the buildings and other constructions surrounding the structure under investigation should be geometrically reproduced, so as to properly model aerodynamic interference.

* + 1. Modelling wind fields over complex orography

(1) Complex orography affects the wind flow and therefore the actions it exerts. The case of a simple 2D orographic feature is considered in Clause 6.3.3. For more complex cases, the effects of orography on local flow can be measured in the wind tunnel using topographic models. These are usually made at a length scale in the order of 1:5000 to 1:1000 and reproduce the area surrounding the structure. They are designed to measure the mean and fluctuating characteristics of the flow at the site. Due to the very small scales, the results can prove inaccurate, and computational simulations can substitute or supplement wind tunnel tests.

NOTE Reynolds number issues and difficulties in reproducing surface roughness at small scales result in poor modelling close to the ground. The characteristics of the flow near the ground can be reproduced in larger scale models (see K.4.3(5)).

(2) The incoming flow should correspond to the flow that would develop at the site in the absence of orography.

(3) Measurements should be carried out by means of anemometers with high sampling frequency and at a sufficient number of points so to reconstruct the special variation of mean and fluctuating features of the flow. Measurement points should preferably be arranged along vertical or horizontal lines, depending on geometry of the structure. The sampling frequency should be at least twice the largest frequency characterising the aerodynamic loading process. The total duration of measurement should be such to provide stable statistics of the mean and fluctuating wind components.

NOTE 1 In addition to anemometry, flow visualisation techniques provide only qualitative information about the flow modifications induced by orography.

NOTE 2 Particle Image Velocimetry (PIV), allowing the measurement of wind velocity field in a given plane, can be used as an alternative, or in addition to anemometry.

(4) The tests should be carried out for different incoming wind directions.

NOTE Angle steps of 10° to 30° are common practice.

(5) The flow characteristics derived from topographic models should then be used to reproduce the incoming flow when testing larger scale models with the aim of deriving aerodynamic parameters or structural response.

* + 1. Pressure measurements

(1) The surface pressure distribution on a structure can be measured in the wind tunnel using a high sampling frequency pressure acquisition system.

NOTE The acquisition system is made of a number of pressure taps located on the surface under investigation, each connected through tubing to a pressure scanner. This converts the pressure signal into an electrical analogue signal that is sent to an analogue-digital converter and then stored on mass memory media.

(2) The accuracy of measured data depends on the characteristics of the entire measurement chain; however, tubing plays a dominant role. Poor tubing design can bring a significant error in the pressure measurements. To ensure acceptable accuracy of measurements, tubing should be able to transfer undistorted pressure fluctuations up to the largest frequency of interest.

(3) The geometric scale of the model (length scale) depends on the dimensions of the structure, or portion of it considered, as well as on the dimensions of the tunnel. The duration of each test should be such to allow adequate statistical processing of the measured data. Measurements should be performed for all critical oncoming wind directions.

NOTE 1 For buildings, the length scale is usually between 1:400 and 1:50, where the first value applies to tall buildings and the second value to low-rise buildings. Larger scales can be used for details, when needed; an example are multiple skin facades, where cavity pressures are needed, provided compensation is made for missing low-frequency turbulence.

NOTE 2 Common angle steps are between 10° and 30°.

(4) The model should be stiff, or otherwise modelled aeroelastically to reflect the true static and dynamic flexibility of the full-scale structure so that the measured pressure takes proper account of fluid-structure interaction.

NOTE Unintended deformations of the model can give rise to errors in the measured pressure.

(5) Buildings and other obstacles surrounding the model under investigation should be reproduced in the wind tunnel, through a proximity model; the extension of the proximity model should be such to properly reproduce relevant aerodynamic interference.

(6) The measured pressure shall be used to obtain the pressure coefficients given by Formula (6.3):

|  |  |
| --- | --- |
|  | (K.1) |

where

|  |  |
| --- | --- |
|  | is time; |
|  | is the measured surface pressure; |
|  | is the reference static pressure; |
|  | is the reference velocity pressure. |

(7) Formula (K.1) can be used to obtain the relevant statistics of the pressure coefficient. The mean value, the standard deviation and the statistical minimum and maximum values can be calculated.

NOTE The minimum and maximum values depend on the time interval in which they are measured and are usually associated with a given probability of exceedance. For example, to define wind loads on a large surface reference is usually made to the mean value of the pressure coefficient. For local loads, reference is usually made to the maximum or minimum peak value of the pressure coefficient.

(8) The sampling frequency should be at least twice the largest frequency characterising the aerodynamic loading process of the structure. Extremes of pressures should be sampled from tests with durations corresponding to the reference duration of the considered storm type. If shorter durations are used, the target probability has to be adjusted accordingly.

(9) The number of pressure taps to be used depends on structural geometry and ranges from a minimum of several dozens to many hundreds. The experimentalist should identify the minimum number of pressure taps to be used to achieve an adequate description of the surface pressure field. The location of pressure taps should be chosen based on structural geometry and flow characteristics; as a general rule, pressure taps should be concentrated more in areas where a higher spatial variation of pressures is expected, i.e. in the vicinity of sharp edges. When the measurements are aimed at evaluating the dynamic response of the structure, the distribution of pressure taps should be consistent with the mode shape of the structure most excited by the wind. Pressure data should be acquired simultaneously and summed for each time step taking account of tributary areas and the particular responses to be determined.

NOTE 1 Tributary area of a given pressure tap is defined as the area of the surface around the tap where the mean and fluctuating pressures are well represented by the measurement at the tap.

NOTE 2 In some cases pressure measurements are needed inside buildings. In this case, a lower number of pressure taps than for external pressures is sufficient. The mean pressure inside a building can be obtained in the wind tunnel in a sufficiently accurate way, provided the porosity of the building is properly reproduced. Reproduction of internal pressure dynamics is more complex and needs support from analytical and/or computational models.

* + 1. Force measurements

(1) Overall loads can be calculated by simultaneous integration of surface pressures. Alternatively, for buildings and other vertical structures, it is possible to use high frequency balance tests.

NOTE 1 If the structure has linearly increasing deflection with height in the first along-wind or across-wind mode, then the measured base bending moment corresponds to the generalised force associated with these modes. The wind tunnel test, therefore, consists in the measurement of the time histories of base bending moments and possibly base shear forces on a rigid model; from these the generalised force spectra in the first two bending modes can be derived. For structures with slightly non-linear mode shapes, correction factors can be applied, accounting for the effective mode shape.

NOTE 2 A similar approach can be applied to the generalised force in the first torsional mode, although the non-coincidence of the torsional mode with a uniform rotation requires the application of correction factors.

NOTE 3 For structures having three-dimensional modes the approach of NOTE 1 and NOTE 2 can bring inaccurate results.

(2) The models used to measure aerodynamic forces must be stiff and have a small mass. The sampling frequency should be at least twice the largest frequency characterising the aerodynamic loading at the lowest and highest wind speeds of interest. Extremes of forces should be sampled from tests with durations corresponding to the reference duration of the considered storm type. If shorter durations are used, the target probability should be adjusted accordingly. Measurements should be performed for all possible oncoming wind directions.

NOTE 1 The model is mounted on a balance capable of measuring force components at the base of the building. The geometric scale (length scale) is usually between 1:400 and 1:100.

NOTE 2 Common angle steps are between 10° and 30°.

(3) Force measurements can also made in the case of bridge decks and in general for all elongated structures characterised by a two-dimensional aerodynamic behaviour. For these structures, the coefficients of force and moment per unit length must be known, should be taken as specified in Formulae (K.2), (K.3) and (K.4):

|  |  |
| --- | --- |
|  | (K.2) |
|  | (K.3) |
|  | (K.4) |

where

|  |  |
| --- | --- |
| , and | are the along-wind and across-wind forces and torque per unit length, respectively; |
| *,* and | are reference dimensions, usually corresponding either to (acrosswind dimension of the section, *breadth*) or (alongwind dimension of the section, *depth*) in the wind tunnel; |
|  | is the reference velocity pressure; |
|  | is the air density in the wind tunnel; |
|  | is the reference wind velocity in the wind tunnel. |

(4) The tests described in (3) are performed on a section model of the structure. The model must be relatively stiff and of low

The sampling frequency should be at least twice the largest frequency characterising the aerodynamic loading. Extremes of pressures should be sampled from tests with durations corresponding to the reference duration of the considered storm type. If shorter durations are used, the target probability should be adjusted.

NOTE The model is mounted on a pair of balances capable of measuring the three components of the load associated with the forces , and . The geometric scale (length scale) depends on the geometric dimensions of the structure or structural element, and on the width of the tunnel test section. When endplates are used in the setup, the length of the model can be shorter than for models with free ends.

(5) Tests on section models of bridge decks and elongated elements do not require reproduction of the actual mean velocity and turbulence intensity profiles; therefore, they can be performed also in aeronautical wind tunnels. Turbulence characteristics, however, should be properly scaled, i.e. that integral length scale in the tunnel must be as close as possible to the full-scale value, reduced through the length scale. In addition to tests in a turbulent regime, tests in smooth flow conditions can be performed. Even though this is an unrealistic condition, it usually provides reference, conservative values of the actions.

(6) Tests on bridge decks should be performed for different angles of attack, so to analyse the effects of small variations in the wind incidence (possibly due to orography effects), and to calculate the angular derivative of the aerodynamic coefficients.

(7) A section model suspended in a stiff rig is used to determine the static force coefficients of the cross section. Forcing movements may also be used to determine aerodynamic admittance functions applied in subsequent analytical buffeting response calculations for the full-scale structure.

(8) For vertical elongated structures, tests should be performed for all possible wind directions, with steps between 1° and 15°. Lower values should be used when the angular derivatives of aerodynamic coefficients are required, especially in cases in which instability phenomena can occur such as galloping, divergence and flutter, see Annex H Larger values apply to elements with a moderate sensitivity to the variation in oncoming flow direction.

(9) Care should be taken to avoid the coupling between the balance and the model, so not to give rise to resonant phenomena. Should this be the case, and should it be impossible to eliminate the cause, analytical procedures should be used to remove resonant components.

* + 1. Measurement of the structural response

(1) Alternative to the measurement of actions (subclauses K.4.4 and K.4.5) to be used for the analytical and/or computational calculation of the structural response, the static and dynamic response of the structure can be directly measured in the wind tunnel.

NOTE When the structural response is directly measured in the wind tunnel, aeroelastic interaction is implicitly accounted for.

(2) To this purpose, flexible (i.e. aeroelastic) models should be used, reproducing the scaled dynamic properties of the actual structure, i.e. the frequencies and modes of vibration, as well as structural damping. Aeroelastic models and testing procedures may be very different from case to case, depending on the structure and on the parameters to be measured. The measured parameters can be either actions or response parameters. If the structural response is measured, the tests must be performed at different wind velocities, so as to analyse possible changes in the response with varying velocity.

(3) For aeroelastic tests, attention should be paid not only to the scaling of length and velocity, but also to that of mass (representing inertia forces) and stiffness (representing elastic forces). Damping should also be accurately reproduced in the modes excited by the wind, making sure that in the wind tunnel it is not higher than in full-scale.

NOTE In most cases, it is not possible to obtain correct scaling of all the physical quantities so it is necessary to use a distorted model, i.e. a model that does not comply with all the scaling requirements. The choice of parameters to be distorted depends on the type of test and strongly affects the quality of the results.

(4) The dynamic properties of the structure are those measured in still air and must be set up before the test.

NOTE In the presence of wind, the dynamic properties of the model vary as a result of the aeroelastic interaction that occurs.

(5) Measurement of the structural response should be performed with accelerometers and/or displacement transducers. The former should be lightweight and wiring should be such not to affect the dynamics of the model. The sampling frequency must be at least twice the largest structural frequency of interest.

NOTE Displacement transducers which are based on laser technology are located outside the model and are not in contact with it. Strain gauges can also be used when measuring displacements.

(6) The following main types of model and tests are generally used:

***Sectional models***. They are models with external elasticity, representing a portion of an elongated structure. The sectional model itself should be rigid, while flexibility and energy dissipation are concentrated in the model supports. Typically, only two or three modes (degrees of freedom) can be considered. They can be used for medium- to long-span bridges, but also for buildings.

***Pivot models***. They are models of vertical structures with external elasticity. The rigid model of the structure (often the same used for base balance tests) should be fitted with a pivot at the base; the pivot connection should reproduces the flexibility and dissipation of the structure. The system obtained can have one, two or three degrees of freedom, and simulates the dynamic behaviour of a structure with linear vibration modes. If these are slightly non-linear, correction factors taking the effective mode shape into account can be applied.

***Aeroelastic replicas***. They are models with internal elasticity, so to reproduce the geometry and the dynamic properties of the entire structure or part of it. They are used for high-rise buildings, medium- and long-span bridges, towers, chimneys, and large-span roofs. The model must be able to reproduce all vibration modes that significantly contribute to the structural response.

***Taut-strip models***. Taut-strip models are used for long-span bridge decks and are based on the reproduction of the bending and torsional stiffness of the deck-cable system through the stiffness deriving from taut cables in the model. Torsional dynamic properties can be difficult to model in full-bridge aeroelastic replicas. Taut-strip models may do best at this, depending on the bridge properties which need to be modelled.

(7) If the action associated with vortex shedding is significant, the full-scale value of the Scruton number should be reproduced in the wind tunnel.

(8) A sectional-model suspended in springs may be used to simulate vertical, torsional and sometimes also lateral vibrations of selected modes of a bridge deck. Besides simulations of the relevant natural frequencies, the modal masses, modal mass moment of inertia and structural damping should also be scaled in accordance with the expected full-scale characteristics. Simulations can cover vortex-induced vibrations for the relevant flow conditions, i.e. low turbulent flow if the wind velocity is below about 15‑20 m/s at full-scale, and turbulent flow for higher wind velocities. The initial tests should be carried out with damping significantly less than expected at full-scale, in order to determine the minimum damping requirement (Scruton Number) to limit the motions. For aeroelastic instabilities where the vertical frequency and torsional frequencies are similar the simulation of the ratio between the vertical and torsional natural frequencies in still air should be accurately reproduced in the wind tunnel. Flutter-induced vibrations may occur at extreme winds, making turbulent flow simulations most relevant. The vibrations experienced at wind velocities approaching the flutter wind velocity may be used to extract flutter derivatives relevant for analytical evaluations of the full-scale buffeting response.

* + 1. Use of wind tunnel data

(1) When aerodynamic coefficients, aerodynamic forces or the structural response based on wind tunnel measurements are used for design calculations, these values should be well documented. In particular, the following information should be clearly provided:

* specifications of the wind tunnel (geometry, dimensions, general characteristics of the flow, etc.)
* type of test(s) performed (aims and measured quantities);
* characteristics of the model (scaling requirements, materials, geometry, masses, dynamic properties, where applicable, etc.)
* characteristics of the flow (mean velocity profile, turbulence intensity profile, turbulence length scale profile, etc.);
* data acquisition protocol (acquisition chain, instrument specifications, sampling frequency, duration, tubing design, where applicable, etc.);
* post processing (analyses performed on the raw data for calculating the aerodynamic coefficients and the design forces, or for calculating the structural response).
  1. Derivation of design parameters from numerical simulations

(1) Computational Fluid Dynamics (CFD) investigates the motion of fluids by means of computational simulations. Computational Wind Engineering (CWE) is the application of CFD techniques to Wind Engineering problems. CWE studies can be used in alternative or to supplement wind tunnel tests.

(2) The features and the accuracy of the computational model shall be such to accurately reproduce the relevant aspects of the physical phenomenon under investigation. No single model exists appropriate to all situations, therefore, the computational model should be adapted to the particular case, as well as the intended use of the results of simulations within the design process.

NOTE The phenomenon of interest and the intended use of the CWE study allow the identification of the class of problem.

(3) The CWE Specialist should have adequate knowledge of both CFD and Wind Engineering, in order to understand the implications of using CFD models in the context of Wind Engineering. In particular, the CWE Specialist should be aware of the approximations of the model and of their potential impact on the results of the CWE study.

NOTE The ability to operate a software dedicated to CFD and/or CWE simulations does not itself qualify the CWE Specialist.

(4) The appropriateness of a computational model can be assessed only by means of relevant validation cases. Such validation cases should systematically compare results obtained by mean of wind tunnel tests and/or full-scale measurements with those obtained using a specific computational model. Such validation should assess the accuracy of the computational model with respect to all the aspects which might influence the results of the CWE study.

(5) In some cases, the accuracy of the computational model can be improved by tuning its parameters. This tuning should generally be avoided and, in any case, supported by systematical sensitivity studies. With reference to a specific class of problem, if validation cases show high sensitivity of the results to such parameters, CWE studies should be used with particular carefulness.

* + 1. Computational model

(1) The following definitions are useful in the description of computational models used in CWE studies.

1. Turbulence — turbulence is a random, inherently three-dimensional, fluctuation of the velocity and pressure fields which, in the case of wind, is typically originated by its interaction with the earth surface and with the obstacles on it. Such fluctuations are subdivided into (a) small-scale fluctuations, whose typical space and time scales are small if compared to the characteristic space and time dimensions of the obstacle and/or of the phenomenon of interest, and (b) large-scale fluctuations, typical space and time scales are comparable with of or larger than the characteristic space and time dimensions of the obstacle and/or of the phenomenon of interest;
2. Turbulence model — mathematical model used to approximate the effects induced by small-scale turbulent fluctuations on the time-averaged flow field and/or on the large-scale turbulent fluctuations;
3. Computational domain — numerical representation of the physical domain in which the flow takes place. The geometry of the physical domain may be simplified under given circumstances. The computational domain should be three-dimensional; two-dimensional domains can be used, provided satisfactorily description is given of the impact of such choice;
4. Initial conditions — state of the flow at the beginning of the computational simulation;
5. Boundary conditions — mathematical representation of the interactions existing between the flow in the computational domain and outside of it. They should be consistent with the class of problem, the flow type and the turbulence model;
6. Discretization method — technique used to transform the set of integro-differential equations which governs the flow into a system of algebraic equations;
7. Numerical schemes — approximation of the differential and/or integral terms of the governing equations discretized by means of the discretization method;
8. Solver — computational algorithm used to solve the algebraic equations obtained by the discretization of the equations governing the flow. It requires specification of appropriate tolerances.

(2) Computational models used in CWE studies are composed of multiple interacting components. Each of such components interacts with the others and contributes to the quality of the simulation. Such components can be subdivided into two main groups:

1. components affecting the physical features that the computational model is able to reproduce (e.g. computational domain dimensionality, use of steady or unsteady formulations, turbulence model, initial conditions, boundary conditions). The ensemble of such components defines the modelling approach;
2. components affecting the accuracy of the approximations introduced when solving equations governing the flow by means of a computer (e.g. spatial and temporal discretization, numerical schemes, solver type and solver tolerances). The ensemble of such components defines the numerical approach.

A schematic view of the subdivision of the components between modelling approach and numerical approach is provided in Figure K.1.

Ein Bild, das Text, Screenshot, Schrift, Zahl enthält.

Automatisch generierte Beschreibung

Figure K.1 — Scheme of the components of a model in CWE

(3) Each component of the computational model should be chosen such to comply with all the others and, as a whole, they need to comply with the class of problem.

NOTE 1 It is not possible to uniquely define a combination of components which is optimal for all cases and, so, their choice and combination is case dependent and not universal.

NOTE 2 The actual ability of the computational model to provide good predictions depends on all components of the modelling approach and of the numerical approach.

NOTE 3 The choice of the components of the modelling approach directly influences the predictive capability of the computational model from a qualitative point of view. The numerical approach mainly determines the computational model accuracy. However, a strong interaction between all components exists so that choices related to the numerical approach can deeply influence the ability of the computational model to reproduce phenomena, even from the qualitative point of view.

(4) The choice of an appropriate turbulence model is of fundamental importance in the setup of CWE studies. Therefore, the turbulence model should be accurately chosen, and all the other model components should be selected accordingly.

NOTE Choice of the turbulence model impacts on the limits of applicability of the computational model

(5) Turbulence modelscan be broadly subdivided into two categories:

1. *non* scale-resolving models, which synthetically take into account the effects of both small and large scales of turbulence, therefore allowing the explicit simulation of the ensemble averaged (or more commonly, time averaged) flow only;
2. scale-resolving models, which synthetically take into account only the effect of small-scale turbulence while allowing to explicitly simulate the large scales.

(6) *In the setup of scale-resolving simulations, it is often important to prescribe appropriate unsteady inlet boundary conditions* in order to ensure that the wind approaching the structure is characterized by appropriate turbulent fluctuations. Such fluctuations should be representative of the turbulence expected at the site of interest. The characteristics of the undisturbed oncoming wind should be assessed not only at the inflow boundary where they are applied, but more importantly as close as possible upstream the construction.

NOTE Non scale-resolving simulations can correctly reproduce the velocity profile of the oncoming wind, but cannot accurately reproduce velocity fluctuations, e.g. turbulence intensity and velocity spectra, even though the simulation is time-dependent.

(7) Computational models should comply with the best practice guidelines used for wind tunnel testing, whenever applicable, and take into consideration the different nature of the two techniques. In such regard, the following features should properly be considered:

1. spatial extension of the computational domain;
2. blockage ratio*;*
3. time length of the simulation in order to provide statistically meaningful results and allow the calculation of effects on structures;
4. effects of similitude criteria (e.g. Reynolds number);
5. modelling the surroundings of the construction; this should explicitly include the site orography when relevant and/or surrounding buildings, if any;
6. number of wind directions and/or angle steps;
7. existence of fluid-structure interaction phenomena;
8. characteristics of the surface of the construction.

(8) Some of the requirements given in this Annex may be relaxed if the CWE study is used only in the preliminary design stage, and if wind tunnel tests or more accurate CWE investigations are planned for the final design stage.

* + 1. Computational model validation

(1) The CWE Specialist should validate the CWE models carefully. The validation process should be defined according to the class of problem of interest. Preliminarily, comparisons between computational results and wind tunnel experimental measurements and/or other simulation results (proven to be effective, stable and accurate) should be performed.

(2) Benchmarking data for model validation should be chosen according to the dominant factors affecting the expected aerodynamic/aeroelastic behaviour, and by ensuring that the ability of the computational model in describing the influence of these factors can be clearly highlighted.

(3) Validation analyses should aim to achieve two main goals:

1. to ensure that the chosen computational model is suitable for describing the addressed application;
2. to provide a quantitative estimate of the accuracy to be expected for the simulated problem.

(4) Benchmarking data should be taken from scientifically and technically qualified sources. Well established and complete databases in terms of experimental conditions and measurements are given in the bibliography.

(5) The computational model should accurately include and reproduce the same conditions in which the reference measurements (experimental and/or numerical) were obtained. Compliance with these requirements should be outlined together with the comparative analysis of the validation results.

(6) Components of the computational model and/or the numerical approach should be varied, within practical ranges, aiming at evaluating their influence on the results.

(7) The comparative analysis between computational results and benchmarking data should involve local quantities in time and in space (e.g. velocity and pressure fields, representative pressure peaks), as well as their high-order statistical moments (e.g. variance), if relevant to the class of problem. Comparisons based on average integral quantities only (e.g. averaged values of the aerodynamic coefficients for the overall structure), although of design interest, cannot be considered as conclusive for validation purposes.

(8) Computational models addressing aeroelastic problems, therefore such to describe both structural and fluid dynamics as well as their interaction, should be validated by referring to each single physics, as well as by addressing benchmarking problems involving fluid-structure interaction phenomena, consistent in terms of time and space scales with the specific application of interest.

* + 1. Using computational simulation data

(1) When aerodynamic coefficients, aerodynamic forces or the structural response based on CWE simulations are used, these values and the computational model should be well-documented. The documentation is not meant to allow full replicability of the simulation, but rather the check of the study. In particular, the following information should be clearly provided:

1. main characteristics of the class of problem and aims of the simulations for the structural design;
2. the collection of the components of the computational model, as specified in K.3.1, complying with the class of problem;
3. type, name and version of the software adopted for the computational simulations;
4. validation study for the computational setup employed for the specific class of problem, justifying the reasons for such a choice;
5. geometry of the problem actually modelled and specific information about the computational grid in space and time (time-step size, spatial mesh resolution near the walls and in other particularly significant regions, etc.);
6. values of the reference quantities (length, area, velocity, frequency, etc.) employed for the normalization of parameters (e.g., Reynolds number or reduced velocity) and results (pressure coefficients, force coefficients, Strouhal number, flutter derivatives, etc.);
7. description of the simulation procedure;
8. characteristics of the flow approaching the structure, also in terms of spatial distribution of quantities of relevance with respect to the turbulence model adopted;
9. checks carried out to assess the accuracy of the simulation (accuracy of the pressure coefficient at stagnation points, undisturbed flow where this is actually expected, etc.);
10. assessment of the convergence in the simulated time frame of the main statistics of some quantities of interest for the specific class of problem.

(2) The level of detail of the documentation should be adequate to the scope of the specific simulations.

1. (informative)  
     
   Guidance on derivation of wind speeds from measurements at meteorological stations
   1. Use of this annex

(1) This Informative Annex provides complementary and supplementary guidance to Clause 6, providing a rational basis on which to determine the fundamental value of the basic wind velocity, using measurements of wind speed.

NOTE National choice on the application of this Informative Annex is given in the National Annex. If the National Annex contains no information on the application of this Informative Annex, it can be used.

* 1. Scope and field of application

(1) The guidance in this Informative Annex is presented so that design wind speeds may be derived from measurements at meteorological stations on a rational basis. This will enable the sharing of wind data, interpolation across national borders and the eventual creation of a single European wind map.

(2) It is intended that the single European wind map will contain contours of 10‑minute mean wind speed at 10 metres above ground level, for basic open terrain. This is the fundamental value of the basic wind velocity, and should be taken as defined in 3.1.1 and 6.2(1).

NOTE 1 Sites in particularly complex, hilly or mountainous terrain can have different wind speeds, together with seasonal and directional variation. Site-specific measurements, modelling and extreme value analysis can be appropriate in such cases.

NOTE 2 Site-specific wind speed measurements, taken for application at that site, do not need to be converted to standard terrain.

(3) The procedures in this Informative Annex do not apply to mixed wind climates (e.g. monsoons, thunderstorms, tornados, etc. …) or non-synoptic winds.

* 1. Wind Speed Records

(1) Wind speed records should be analysed using the statistical theory of extreme values or parent population methods. For statistically reliable results, wind speed records should cover periods of 20‑years or longer. Only complete years of data should be used. A “year” should be taken as a 12‑month period, typically from mid-summer to mid-summer; all data for the windiest season should fall within the same “year”.

NOTE 1 Wind speed records for use at (or in close proximity to) one specific measurement site can be for a shorter period, if correlated with data from nearby site(s) with sufficiently long-term statistics.

NOTE 2 If prediction of wind speeds for individual direction sectors is required, the analysis method for individual storms (or other suitable methods) should be used. The largest possible data sets should be used, with extreme value analyses repeated periodically as more records are collected.

(2) Before undertaking an extreme value or parent population analysis, anemometer data should be audited to ensure it is of sufficient and consistent quality. Issues to address may include changes in:

* surroundings over the record period (e.g. construction, tree growth, etc.)
* anemometer type (e.g. from pressure tube to rotating cup)
* recording methodology (e.g. from manual to automatic)
* anemometer location
* self-consistency of the data (e.g. unexplainable variability).

Calibration of anemometers should also be verified.

(3) When auditing wind data records, it should be established whether values have been allocated to bins of a given range or rounded, resulting in significant numbers of records with the same value. Such data should be randomised, or the method of extreme value or parent population analysis adapted to suit.

(4) Wind data records from different anemometer sites should be transposed to basic open terrain by applying exposure corrections for altitude, terrain roughness and orography. These factors are almost always dependent on wind direction.

(5) Adjustments for variations in windward terrain roughness should be undertaken.

The equilibrium wind profiles given in prEN 1991‑1‑4 are not suitable for this purpose. It takes many tens of kilometres to establish an equilibrium wind profile at the reference height of 10m. Methods such as those in the ESDU Wind Engineering Data Item 84011 and ESDU Wind Engineering Data Item 87034 should be used to account properly for varying fetches of upstream roughness and give the appropriate non-equilibrium wind profile.

(6) The standard reference height for wind speed measurement is 10 m above ground level. Corrections should be applied to data from anemometers at other heights.

(7) Anemometers may record mean and/or gust wind speeds. The basis of prEN 1991‑1‑4 is the 10‑minute mean wind speed, which should be taken as the mean value of each consecutive 10‑minute period. Where anemometers record at different averaging periods (e.g. hourly-mean) data should be analysed as is, and then transposed to the 10‑minute mean basis.

NOTE The 10-minute mean wind speed can be taken as 1.06 times the hourly-mean wind speed.

(8) Variation in mean flow over local orography may be assessed by computational methods, wind tunnel testing or codified methods, as appropriate. Care should be exercised when considering orography with slopes steeper than about 0,3, as separation of flow may occur, which may be highly sensitive to modelling assumptions and may (also at full-scale) be erratic.

(9) Data from anemometers close to significant obstructions which may result in blockage, funnelling or local acceleration of flow should not be used, without additional supporting data.

* 1. Extreme Value or Parent Population Analysis

(1) The methods of analysis used to predict the fundamental value of the basic wind velocity, 𝑣b,0 are a National choice. Possible methods include Extreme Value Analysis using asymptotic forms, Extreme Value Analysis using penultimate distributions, the Peak Over Threshold method and parent population methods. When applying Extreme Value Analysis, use of the Fisher-Tippet Type I distribution is preferred. Annual, monthly or storm maxima can be used for Extreme Value Analysis.

(2) The application of several methods to the wind speed data is recommended.

NOTE Mean wind speeds are sensitive to assessment of aerodynamic ground roughness. Gust wind speeds are less sensitive to aerodynamic ground roughness but are sensitive to the type of anemometer used and method of data filtering applied. Where windward aerodynamic ground roughness is difficult to assess, EVA of gust wind speeds can additionally be undertaken.

(3) The basic mean wind population of synoptic winds in Europe is represented sufficiently by a Weibull distribution. The cumulative distribution function of the extremes of a Weibull distribution will converge towards a Fisher-Tippett Type‑I (FT‑I) distribution.

1. (informative)  
     
   Guidance on probabilistic description of wind actions
   1. Use of this annex

(1) This Informative Annex provides specific guidance on probabilistic description of wind actions, in addition to the general guidance given in EN 1990:2023, Annex C Reliability analysis and code calibration and Annex D Design assisted by testing.

NOTE National choice on the application of this Informative Annex is given in the National Annex. If the National Annex contains no information on the application of this Informative Annex, it can be used.

* 1. Scope and field of application

(1) This Informative Annex describes how to determine the characteristic values of wind actions when the statistical distributions of their terms are known.

* 1. Probabilistic variables

(1) Wind actions are defined in Clause 7 of this document, by expressions such as:

* wind pressure acting on the external surfaces, Formulae (7.2), (6.10):
* quasi-static peak wind force acting on a structure, Formulae (7.4) + (6.10):

In these expressions, each term may be represented by a random variable having a statistical distribution, a mean value and a standard deviation.

The basic velocity pressure is its annual extreme value having a 2 % probability of being exceeded.

Its probability distribution function is a Type I extreme-value distribution should be taken from Formula (M.1):

|  |  |
| --- | --- |
|  | (M.1) |

its mean value should be taken from Formula (M.2):

|  |  |
| --- | --- |
|  | (M.2) |

and its standard deviation should be taken from Formula (M.3):

|  |  |
| --- | --- |
|  | (M.3) |

where and are the mode and the scale parameters of the distribution.

(2) In this document, the other terms are defined in a deterministic way by normative values, so that the calculated values of the wind actions (pressures or forces) may be considered to be also annual extreme values having a 2 % probability of being exceeded.

However, when these other terms (or some of them) are known by their statistical distribution, in principle, the probability that the characteristic values of the calculated wind actions are exceeded should be the same as for the basic velocity pressure, i.e. annual extreme values having a 2 % probability of being exceeded.

Consequently, the values of these other terms calculated by using their statistical distribution should be calibrated accordingly.

* 1. Calibration of the values of the terms on basis of their statistical distribution

The probability levels of the terms calculated by using their statistical distribution should be calibrated in order to keep the same probability level for the calculated value of the wind actions as for the basic velocity pressure .

The values of these calibrated probability levels will depend on the knowledge of the statistical distribution of these terms.

Bibliography

**References contained in recommendations (i.e. “should” clauses)**

The following documents are referred to in the text in such a way that some or all of their content constitutes highly recommended choices or course of action of this document. Subject to national regulation and/or any relevant contractual provisions, alternative documents could be used/adopted where technically justified. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 1993-1-11, *Eurocode 3 — Design of steel structures — Part 1-11: Tension components*

EN 1993-3, *Eurocode 3 — Design of steel structures — Part 3: Towers, masts and chimneys*

ESDU 84011, *Wind speed profiles over terrain with roughness changes*

ESDU 87034, *World-wide extreme wind speeds. Part 1: origins and methods of analysis*

**References contained in permissions (i.e. “may” clauses)**

The following documents are referred to in the text in such a way that some or all of their content expresses a course of action permissible within the limits of the Eurocodes. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

None

**References contained in possibilities (i.e. “can” clauses) and notes**

The following documents are cited informatively in the document, for example in “can” clauses and in notes.

EN 1991-1-3, *Eurocode 1 — Actions on structures — Part 1-3: Snow loads*

EN 1991-1-6, *Eurocode 1 — Actions on structures — Part 1-6: Actions during execution*

prEN 1991-1-9, *Eurocode 1 — Actions on structures — Part 1-9: Atmospheric icing*

EN 1991‑2, *Eurocode 1 — Actions on structures — Part 2: Traffic loads on bridges and other civil engineering works*

EN 1993-1-1, *Eurocode 3 — Design of steel structures — Part 1-1: General rules and rules for buildings*

EN 12811‑1, *Temporary works equipment — Part 1: Scaffolds — Performance requirements and general design*

CEN/TS 19100-2, *Design of glass structures — Part 2: Design of out-of-plane loaded glass components*