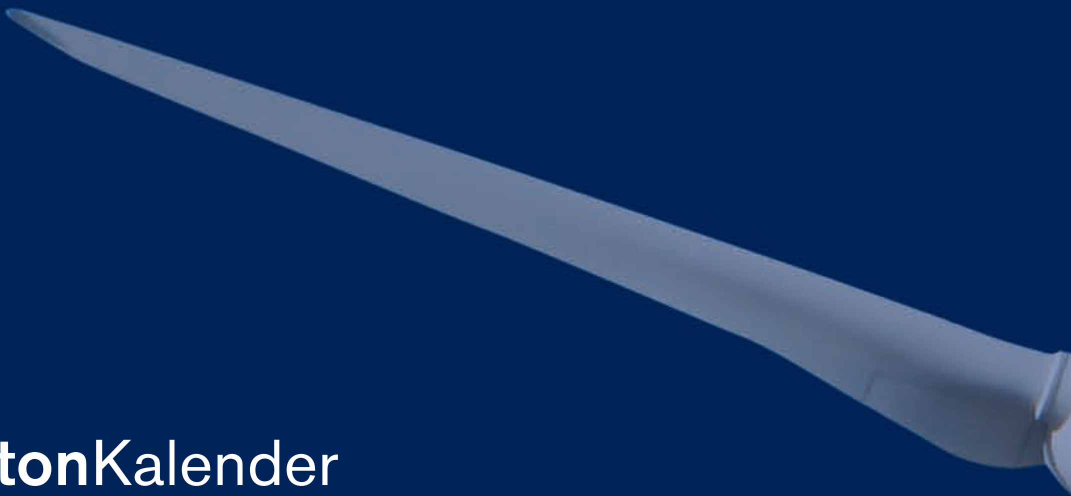

BetonKalender

Concrete Structures for Wind Turbines

Jürgen Grünberg, Joachim Göhlmann

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Concrete Structures
for Wind Turbines

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The Authors

Prof. Dr.-Ing. Jürgen Grünberg
Flerrentwiete 79
22559 Hamburg
Germany

Dr.-Ing. Joachim Göhlmann
grbv Ingenieure im Bauwesen GmbH & Co. KG
Expo Plaza 10
30539 Hannover
Germany

The Editors of Beton-Kalender

Prof. Dipl.-Ing. Dr.-Ing. Konrad Bergmeister
Ingenieurbüro Bergmeister
Peter-Jordan-Straße 113
1190 Vienna
Austria

Dr.-Ing. Frank Fingerloos
German Society for Concrete and Construction Technology
Kurfürstenstr. 129
10178 Berlin
Germany

Prof. Dr.-Ing. Dr. h.c. mult. Johann-Dietrich Wörner
German Aerospace Center
Linder Höhe
51145 Cologne
Germany

Translation by: *Philip Thrift, Hannover,* Germany

Coverphoto: Mathias Euler, Stuttgart, Germany

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Contents

Editorial

The "Concrete Yearbook" is a very important source of information for engineers involved in design, analysis, planning and production of concrete structures. It is published on a yearly basis and offers chapters devoted to various subjects with high actuality. Any chapter gives extended information based on the latest state of the art, written by renowned experts in the areas considered. The subjects change every year and may return in later years for an updated treatment. This publication strategy guarantees, that not only the most recent knowledge is involved in the presentation of topics, but that the choice of the topics itself meets the demand of actuality as well.

For decades already the themes chosen are treated in such a way, that on the one hand the reader is informed about the backgrounds and on the other hand gets acquainted with practical experience, methods and rules to bring this knowledge into practice. For practicing engineers, this is an optimum combination. Engineering practice requires knowledge of rules and recommendations, as well as understanding of the theories or assumptions behind them, in order to find adequate solutions for the wide scope of problems of daily or special nature.

During the history of the "Concrete Yearbook" an interesting development was noted. In the early editions themes of interest were chosen on an incidental basis. Meanwhile, however, the building industry has gone through a remarkable development. Where in the past predominantly matters concerning structural safety and serviceability were in the centre of attention, nowadays an increasing awareness develops due to our responsibility with regard to society in a broader sense. This is reflected e.g. by the wish to avoid problems related to limited durability of structures. Expensive repair of structures has been, and unfortunately still is, necessary because of insufficient awareness of deterioration processes of concrete and reinforcing steel in the past. Therefore structural design should focus now on realizing structures with sufficient reliability and serviceability for a specified period of time, without substantial maintenance costs. Moreover we are confronted with a heritage of older structures that should be assessed with regard to their suitability to safely carry the often increased loads applied to them today. Here several aspects of structural engineering have to be considered in an interrelated way, like risk, functionality, serviceability, deterioration processes, strengthening techniques, monitoring, dismantlement, adaptability and recycling of structures and structural materials, and the introduction of modern high performance materials. Also the significance of sustainability is recognized. This added to the awareness that design should not focus only on individual structures and their service life, but as well on their function in a wider context, with regard to harmony with their environment, acceptance by society, the responsible use of resources, low energy consumption and economy. Moreover the construction processes should become cleaner, with less environmental nuisance and pollution.

The editors of the "Concrete Yearbook" have clearly recognized those and other trends and offer now a selection of coherent subjects which resort under a common "umbrella" of a broader societal development of high relevance. In order to be able to cope with the corresponding challenges the reader is informed about progress in technology, theoretical methods, new findings of research, new ideas on design and execution, development in production, assessment and conservation strategies. By the actual selection of topics and the way those are treated, the "Concrete Yearbook" offers a splendid opportunity to get and stay aware of the development of technical knowledge, practical experience and concepts in the field of design of concrete structures on an international level.

Prof. Dr. Ir. Dr.-Ing. h.c. *Joost Walraven*, TU Delft
Honorary president of the international concrete federation *fib*

1 Introduction

The wind energy industry in Germany has an excellent global standing when it comes to the development and construction of wind turbines. Germany currently represents the world's largest market for wind energy. So far, more than 21 000 wind turbines with a total output of approx. 25 000 MW have been installed across the country. And at the moment that figure is growing by approx. 2000 MW every year [1]. Developments in land-based installations are moving in the direction of more powerful turbines with more than 3 MW per installation and towers exceeding 140 m in height.[1)]

However, the number of lucrative sites on land (onshore) is dwindling. Therefore, it is planned to construct wind turbines at sea (offshore) in the coming years. The plans provide for offshore wind farms in the North Sea and Baltic Sea and are intended to increase substantially the proportion of renewable energies in electricity generation. The target for the medium-term is installations in the North Sea and Baltic Sea with a total output amounting to some 3000 MW. By 2030 it is hoped that offshore wind turbines with a total output of about 20 000 to 25 000 MW will have been built [2].

Figure 1.1 shows the results of a study carried out by DEWI, the German Wind Energy Institute. It shows the annual installed wind energy output for each year since 1990 plus the forecast up to the year 2030. According to the study, the decline in onshore installations should be compensated for by the anticipated development in offshore

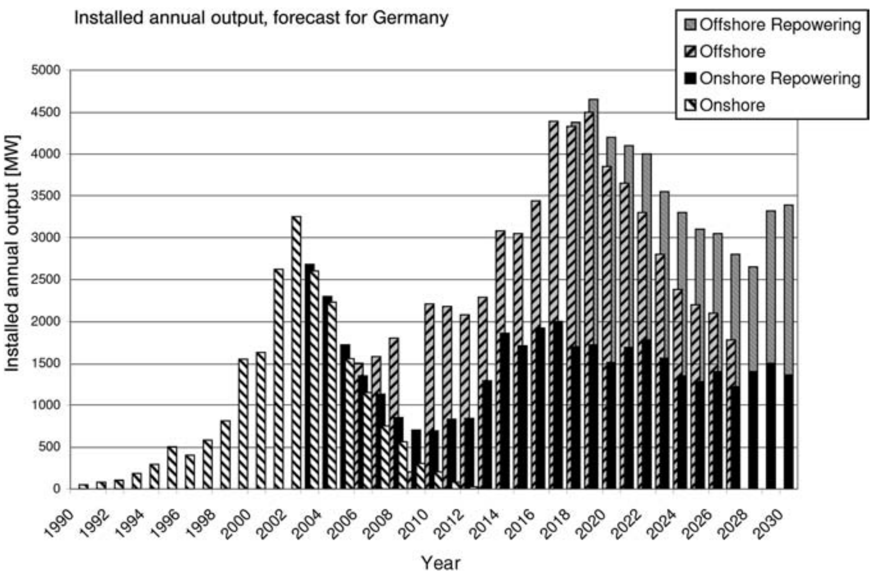

Fig. 1.1 Installed wind energy output per year in Germany [3]

1) Source: Bundesverband der Windenergie e.V. (www.wind-energie.de).

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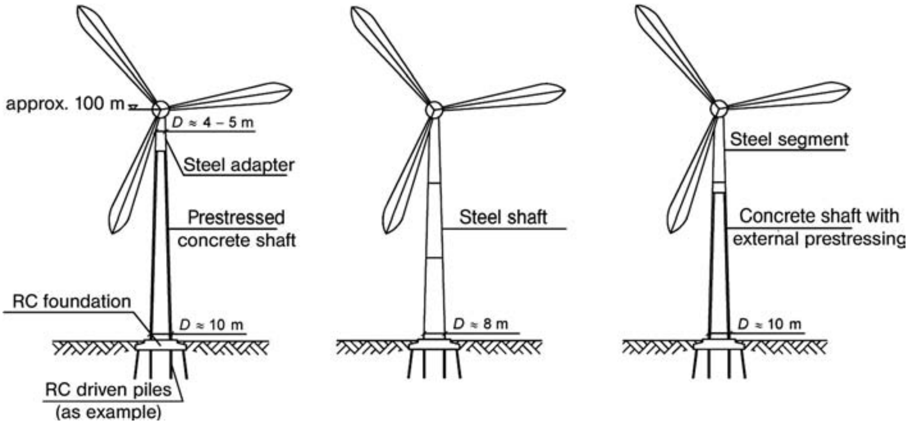

Fig. 1.2 Typical onshore tower designs for wind turbines

wind farms and by the repowering of land-based installations, leading to a doubling in the annual installed output by the year 2020.

The towers supporting onshore wind turbines are mainly of steel or prestressed concrete with internal or external prestressing. Steel lattice masts are also used in isolated instances. The prestressed concrete towers make use of both *in situ* and precast concrete. In recent years, the use of hybrid towers, consisting of a prestressed concrete shaft and a steel top section, has proved to be a very economical solution, especially for wind turbines in the multi-megawatt category. The choice of a suitable tower design is governed by the conditions at the site (fabrication, transport, erection, etc.). Figure 1.2 illustrates typical towers for onshore wind turbines.

Both shallow and deep foundations can be used for onshore wind turbines. Soil improvement measures can be employed to upgrade subsoil properties to those required for shallow foundations [4, 5]. Driven piles of steel or concrete with appropriate toe forms are frequently used as deep foundations.

So far, about 25 wind farms have been approved for construction off the German coast in the North Sea and Baltic Sea within the 12-mile zone and the exclusive economic zone (EEZ) for water depths of up to 45 m. But the better wind conditions at sea call for a greater technical input for the loadbearing structure and the fabrication and erection of the wind turbines [6]. Besides the depth of the water, the choice of a suitable offshore structure is especially dependent on the wave and current conditions plus the subsoil beneath the seabed. Concrete structures in the form of gravity bases are economic propositions for nearshore sites and for greater depths of water, see [7]. Such foundations are built in a dock, for example, then floated out to their final position and sunk. Resolved designs with individual members made from prestressed high-strength concrete are also feasible. An overview of the offshore foundation concepts currently under discussion can be found in Section 5.

The ongoing development of ever more powerful wind turbines plus additional requirements for the design and construction of their offshore foundation structures exceeds the actual experience gained so far in the various disciplines concerned. Wind turbines represent structures subjected to highly dynamic loading patterns. The load cycles of onshore installations can reach $N = 10^9$, but those of offshore installations can be exposed to further load cycles of up to $N = 10^8$ due to the sea conditions. Therefore, for the design of loadbearing structures, fatigue effects – and not just maximum loads – are extremely important. This can lead, in particular, to multi-axial stress states arising in the connections and joints of concrete and hybrid structures (see Sections 3.6 and 4.9), which have considerable effects on the fatigue strength and so far have not been addressed in the applicable design codes.

On the whole, there is still a great need for further research in the various disciplines involved in the planning, design and construction of wind turbines. It was for this reason that the Centre for Wind Energy Research *ForWind* (www.forwind.de) was set up at the Carl von Ossietzky University of Oldenburg and the Leibniz University of Hannover in 2003, thus enabling engineers from different disciplines to work together on research into wind energy. Supported by the Lower Saxony Ministry of Science and Culture, the objective of the centre is to pool research activities. Construction technology research into offshore wind turbines began at the University of Hannover as long ago as 2000 in the shape of the *GIGAWIND* (www.gigawind.de) joint project sponsored by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. These research activities are divided into three areas: actions due to wind and waves, design of loadbearing structures (including foundations) and environmental technology aspects. *GIGAWIND alpha ventus* is a project associated with the *RAVE* (***R**esearch at **A**lpha **V**entus*) research initiative and therefore has access to the extensive programme of measurements carried out at the Alpha Ventus test site, Germany's first offshore wind farm. At European level, the University of Hannover participates in the *European Academy of Wind Energy* (www.eawe.eu). The objective here is to promote research and development and to train PhD students in the field of wind energy in various European countries.

The basic concepts for the planning, design, analysis and construction of tower structures, focusing on wind turbines especially, will be explored in the next chapters.

Many aspects of these basic concepts also apply to the structural and constructional requirements of other tower-type structures, for example

– telecommunications towers
– radar towers and lighthouses in shipping lanes
– antenna support structures and masts for mobile telephone networks
– chimneys

For more information on these structures please refer to *Beton-Kalender 2006 Teil 1*, pp. 103–223 [8].

2 Actions on wind turbines

2.1 Permanent actions

In addition to the typical dead loads of the plant (rotor and nacelle) and the structure (tower and foundation), there are also other loads that are classed as permanent actions: for example the loads of items fitted inside the tower (cables, intermediate platforms, etc.), and those due to further electrical equipment, for example transformers, ventilation systems.

And when it comes to offshore wind turbines there are yet further dead loads to be considered such as external platforms, boat moorings or cathodic corrosion protection.

For the dynamic analysis in particular, the masses of the individual items and components must be known and taken into account accurately in the design.

2.2 Turbine operation (rotor and nacelle)

The actions due to the operation of the turbine are determined by means of numerical simulations (see also Section 4.9.1). In addition to various wind load models, with the superposition of wave action effects where applicable, such simulations must also take into account particular operating situations, for example starting and stopping procedures.

The load case combinations to be investigated are laid down in the relevant codes and guidelines, for example the DIBt guideline for onshore wind turbines [9], see Section 4.5.3, and DIN EN 61400-3 for offshore wind turbines [10]. Load combinations are also defined in the guidelines published by a number of certification bodies, for example the *GL Guideline* [11], see Section 4.6.4.

Note: The *GL Guideline* for offshore wind turbines [11] is based on *Rules and Guidelines, IV Industrial Services – 1 Guideline for the Certification of Wind Turbines* dating from 2003/04, which in July 2010 was republished in a revised edition.

2.3 Wind loads

2.3.1 Wind loads for onshore wind turbines

According to DIN 1055-4 [12], the environmental conditions in Germany (including the German Bight) can be divided into four wind zones (Figure 2.1).

The reference values (v_{ref}; q_{ref}) in the table are valid for

- averaging over a period of 10 min,
- a 0.02 probability of being exceeded in one year,
- a height of 10 m above ground level,
- flat, open terrain, which corresponds to terrain category II in DIN 1055-4 annex B.

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Wind zone	v_{ref}	q_{ref}
WZ 1	22.5 m/s	0.32 kN m^2
WZ 2	25.0 m/s	0.39 kN m^2
WZ 3	27.5 m/s	0.47 kN m^2
WZ 4	30.0 m/s	0.56 kN m^2

Fig. 2.1 Wind zones to DIN 1055-4 [12]

The relationship between reference values for wind speed v_{ref} and dynamic pressure q_{ref} is given by the following equation:

$$q_{ref}[kPa] = \frac{(v_{ref}[m/s])^2}{1600}$$

When designing towers, only the reference dynamic pressures for terrain categories II (inland) or I (wind zone 4 directly on the coast) should be assumed. Less onerous terrain categories (III and higher) can be ruled out because the effects of the various ground roughnesses decrease as the height of the structure increases.

Therefore, the combined profiles given in DIN 1055-4 [12] for structures up to 50 m in height should not be used either (see also *Beton-Kalender 2006* [8]).

Prior to the introduction of DIN 1055-4 [12], the wind loads for tower-type structures were calculated according to DIN 1056 [13] or annex A of DIN 4131 [14] or annex A of DIN 4228 [15]. *Beton-Kalender 2006* [8] compares the wind loads according to the old standards and DIN 1055-4 [12].

2.3.1.1 Wind loads according to the DIBt guideline

According to DIN 1055-4, the following basic parameters apply (see Figure 2.2 and Table 2.1):

– 50-year return wind v_{m50} (z)
– 50-year return gust v_{e50} (z)

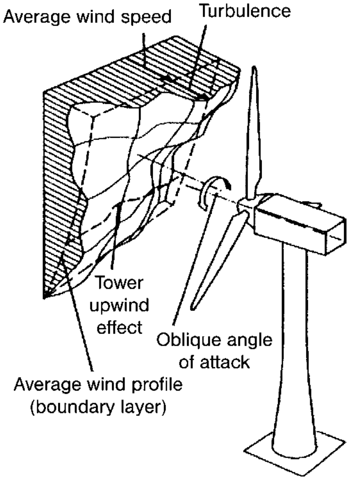

Fig. 2.2 Angle of attack for the rotor of a wind turbine

Table 2.1 Wind conditions for onshore wind turbines in terrain category II according to [12]

Basic parameters according to DIN 1055-4 [12][a)]					Unit	Remarks
Wind zone	WZ 1	WZ 2	WZ 3	WZ 4		
v_{m50} (= v_{ref})[b)]	22.5	25.0	27.5	30.0	m/s	50-year return wind, 10-min average
$v_{e50} = 2.1^{0.5} \cdot v_{m50}$	32.6	36.2	39.9	43.5	m/s	50-year return wind, 2–4 s gust
$v_{m1} = 0.8 \cdot v_{m50}$	18.0	20.0	22.0	24.0	m/s	1-year return wind, 10-min average
$v_{e1} = 0.8 \cdot v_{e50}$	26.1	29.0	31.9	34.8	m/s	1-year return wind, 2–4 s gust
Additional parameters according to DIBt guideline [9] for dynamic analyses						
$V_{ave} = 0.18 \cdot v_{m50}\,(h) = 0.18 \cdot v_{ref} \cdot (h/10)^{0.16}$					m/s	Annual average wind speed at hub height h [m]
$I_{15,A} = 0.18$					—	Average turbulence intensity, class A, for $V_{hub} = 15$ m/s
$a_A = 2$					—	Slope parameter for turbulence characteristics

a) z = 10 m above ground level, terrain category II, site altitude ≤ sea level + 800 m
b) According to [16], V_{ref} (capital V) denotes the wind speed of the 50-year return wind at hub height h.

- 1-year return wind v_{m1} (z)
- 1-year return gust V_{e1} (z)

Additional parameters (DIBt guideline [9]):

- Annual average wind speed v_{ave}
- Average turbulence intensity I_{15}
- Verification of the wind turbine for compliance with the turbulence intensity of turbulence category A according to [16].

2.3.1.2 Checking the susceptibility to vibration

According to DIN 1055-4 [12] Section 10, the wind forces acting on structures not susceptible to vibration are based on the *peak dynamic pressure*, which is averaged over a gust duration of 2–4 s (Table 2.2).

According to DIN 1055-4 [12] 6.2 (2), the wind loads for structures acting as cantilevers may be determined according to the simplified method for structures not susceptible to vibration (see below) provided the following condition is satisfied:

$$\frac{x_s}{h} \leq \frac{\delta}{\left(\sqrt{\frac{h_{ref}}{h}} \cdot \frac{h+b}{b} + 0.125 \cdot \sqrt{\frac{h}{h_{ref}}}\right)^2} \quad \text{with} \quad h_{ref} = 25\,\text{m}$$

where

x_s displacement of top of structure under dead load assumed to act in the direction of the wind [m]
δ logarithmic damping decrement according to annex F
b width of structure [m]
h height of structure [m].

Table 2.2 Peak dynamic pressure (to DIN 1055-4 [12] Table B.2)

$q_B(z_j) = \mathbf{c} \cdot q_{ref} \cdot (z_j/10)^{\mathbf{d}} \quad (\text{or} \quad \mathbf{c}_{min} \cdot q_{ref} \quad \text{for } z_j < z_{min})$

Terrain category	I	II	III	IV
Factor **c**	2.6	2.1	1.6	1.3
Exponent **d**	0.19	0.24	0.31	0.40
z_{min}	2.00	4.00	8.00	16.00
$\mathbf{c}_{min}$	1.9	1.7	1.5	1.3

2.3.1.3 Example of application

Prestressed concrete wind turbine structure, hub height 130 m (see Section 5.2):

$$\frac{\delta}{\left(\sqrt{\frac{h_{ref}}{h}\cdot\frac{h+b}{b}}+0.125\cdot\sqrt{\frac{h}{h_{ref}}}\right)^2}=$$

$$\frac{0.04}{\left(\sqrt{\frac{25}{129.7}\cdot\frac{129.7+5.6}{5.6}}+0.125\cdot\sqrt{\frac{129.7}{25}}\right)^2}=\frac{0.04}{\left(\sqrt{4.66}+0.125\cdot\sqrt{5.19}\right)^2}=0.0067$$

$$x_s/h = y_{36}/(z_{36}-z_1) = 4.274/(130.174-0.500) = 0.0330 > 0.0067$$

The tower is therefore susceptible to vibration.

According to [9] 8.3.1, the vibration effect of the tower in the direction of the wind caused by the gustiness of the wind for a wind turbine in the "non-operational" condition (see Section 4.5.2) must be taken into account by way of an equivalent static load, which according to [9] Section B.3 or DIN 1055-4 [12] annex C may be calculated as follows:

Resultant equivalent static wind load in structure segment j ([12] C.2)

$$F_{Wj} = G\cdot c_{fj}\cdot q_m(z_j).A_j$$

where

G	gust response factor to DIN1055-4 [12] C.3
c_{fj}	aerodynamic force coefficient for segment i to DIN 1055-4 [12] 12.6 or 12.7
$q_m\ (z_j)$	average dynamic pressure at location z_j
z_j	average height of segment j above ground level
A_j	reference area of segment j

Average dynamic pressure (10-min average) ([12] C.2 (3))

$$q_m(z_j) = \frac{\rho}{2}\cdot\left[v_m(z_j)\right]^2 \quad \text{or} \quad q_m[\text{kPa}] = \frac{(v_m[\text{m/s}])^2}{1600}$$

ρ density of air: $\rho = 1.25\,\text{kg/m}^3$
v_m average wind speed (Table 2.3)

Table 2.3 Average wind speed (to DIN 1055-4 [12] Table B.2).

$\mathbf{v}_m(z_j) = \mathbf{a}\cdot\mathbf{v}_{ref}\cdot(z_j/10)^{\mathbf{b}}$ (or $\mathbf{a}_{min}\cdot\mathbf{v}_{ref}$ for $z_j < z_{min}$)

Terrain category	I	II	III	IV
Factor **a**	1.18	1.00	0.77	0.56
Exponent **b**	0.12	0.16	0.22	0.30
z_{min}	2.00	4.00	8.00	16.00
$\mathbf{a}_{min}$	0.97	0.86	0.73	0.64

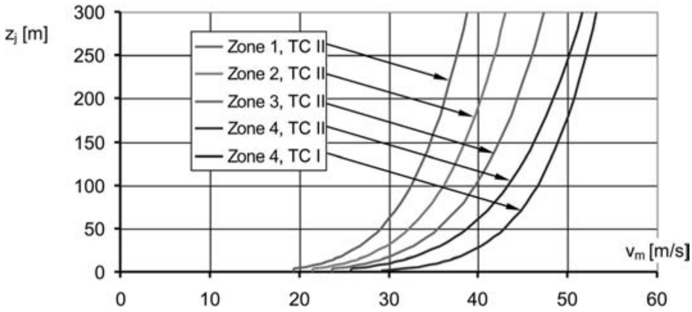

Fig. 2.3 Average wind speeds for various wind zones

Figure 2.3 shows the associated wind speed profiles.

The *gust response factor* (G) is related to the average dynamic pressure q_m. DIN 1055-4 [12] C.3 (1) contains the following formula:

$$G = 1 + 2 \cdot g \cdot I_v(z_e) \cdot \sqrt{Q_0^2 + R_x^2}$$

where

I_v (z_e) turbulence intensity at effective height z_e (Table 2.4)
z_e reference height (see DIN 1055-4 [12] Figure C.1) [m] ($z_e = 0.6 \cdot h$ applies for towers of height h)
g peak factor
Q_0 quasi-static component (basic gust component) of gust response
R_x resonance component of response as a result of gust response

These parameters are explained below.

Figure 2.4 shows the associated turbulence intensity profiles.

Table 2.4 Turbulence intensity (to DIN 1055-4 [12] Table B.2)

$I_v(z_e) = \mathbf{e} \cdot (z_e/10)^{\mathbf{f}}$ (or $I_{v,max}$ for $z_e < z_{min}$)				
Terrain category	I	II	III	IV
Factor **e**	0.14	0.19	0.28	0.43
Exponent **f**	−0.12	−0.16	−0.22	−0.30
z_{min}	2.00	4.00	8.00	16.00
$I_{v,max}$	0.20	0.22	0.29	0.37

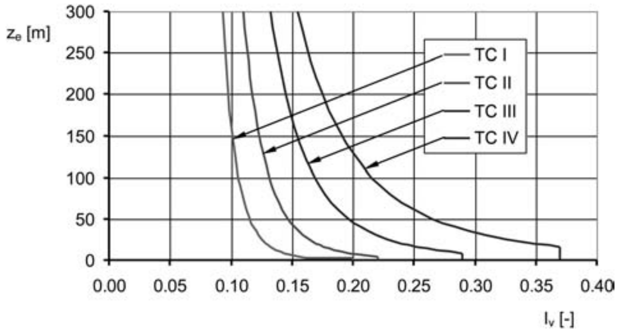

Fig. 2.4 Turbulence intensities for various terrain categories

Peak factor (Figure 2.5) according to DIN 1055-4 [12] C.3 (2):

$$g = \sqrt{2 \cdot \ln(\nu_E \cdot t)} + \frac{0.6}{\sqrt{2 \cdot \ln(\nu_E \cdot t)}}$$

where

t averaging period for reference wind speed v_{ref}: $t = 600\,s$ (= 10 min)

Expected value for frequency of gust response to DIN 1055-4 [12] C.3 (3):

$$\nu_E = \sqrt{\frac{\nu_{E,0}^2 \cdot Q_0^2 + n_{1,x}^2 \cdot R_x^2}{Q_0^2 + R_x^2}}$$

where

$n_{1,x}$ first natural frequency [Hz] of structure vibration in direction of wind (x direction)

$\nu_{E,0}$ expected value of frequency [Hz] of gust response of structure assuming a quasi-static structural behaviour:

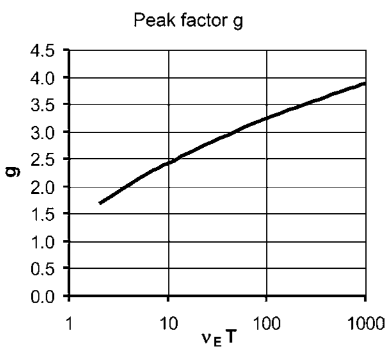

Fig. 2.5 Peak factor

Table 2.5 Integral length L_i (z) of turbulence (to DIN 1055-4 [12] C.3 (4))

$L_i(z) = 300 \cdot (z/300)^{\varepsilon}$ (L_i, z in m) for $z_{min} \leq z \leq 300$ m
$L_i(z) = 300 \cdot (z_{min}/300)^{\varepsilon}$ (L_i, z_{min} in m) for $z \leq z_{min}$

Terrain category	I	II	III	IV
Exponent ε	0.13	0.26	0.37	0.46
z_{min}	2.00	4.00	8.00	16.00

$$\nu_{E,0} = \frac{v_m(z_e)}{L_i(z_e)} \cdot \frac{1}{1.11 \cdot S^{0.615}}$$

where

$$S = 0.46 \cdot \frac{b+h}{L_i(z_e)} + 10.58 \cdot \frac{\sqrt{b \cdot h}}{L_i(z_e)}$$

b, h width, height of structure to DIN 1055-4 [12] Figure C.1
v_m (z_e) average wind speed at effective height $z = z_e$ (see above) to DIN 1055-4 [12] Table B.2 (see above)
L_i (z_e) integral length of longitudinal component of turbulence in direction of average wind for $z = z_e$ (Table 2.5)

Basic gust component Q_0, squared ([12] C.3 (5))

$$Q_0^2 = \frac{1}{1 + 0.9 \cdot \left(\frac{b+h}{L_i(z_e)}\right)^{0.63}}$$

Resonance response component R_x, squared ([12] C.3 (6))

$$R_x^2 = \frac{\pi^2}{2 \cdot \delta} \cdot R_N \cdot R_h \cdot R_b$$

where

δ logarithmic damping decrement for vibrations in wind direction to DIN 1055-4 [12] annex F

Dimensionless spectral density function R_N ([12] C.3 (7))

$$R_N = \frac{6.8 \cdot N_{1,x}}{(1 + 10.2 \cdot N_{1,x})^{5/3}}$$

where

$$N_{1,x} = \frac{n_{1,x} \cdot L_i(z_e)}{v_m(z_e)}$$

Aerodynamic transfer functions R_h and R_b ([12] C.3 (8))

These are specified for the fundamental vibration mode with identical sign (deformation in the same direction) and are calculated, starting from R_L, as follows:

$$R_L = \frac{1}{\eta} - \frac{1}{2 \cdot \eta^2} \cdot \left(1 - e^{-2 \cdot \eta}\right) \quad \text{for} > 0$$
$$R_L = 1 \qquad \text{for} = 0$$

where

$$R_h = R_L \quad \text{with} \quad \eta_h = \frac{4.6 \cdot N_{1,x} \cdot h}{L_i(z_e)}$$

$$R_b = R_L \quad \text{with} \quad \eta_b = \frac{4.6 \cdot N_{1,x} \cdot b}{L_i(z_e)}$$

Logarithmic damping decrement δ ([12] F.5)

Estimate of the logarithmic damping decrement for the fundamental flexural vibration mode to DIN 1055-4 [12] F.5 (1):

$$\delta = \delta_s + \delta_a + \delta_d$$

Structural damping δ_s see Table 2.6.

Aerodynamic damping ([12] F.5 (3))

$$\delta_a = \frac{\rho \cdot b \cdot c_f}{2 \cdot n_{1,x} \cdot m_{1,x}} \cdot v_m(z_e)$$

where

ρ density of air: $\rho = 1.25\,\text{kg/m}^3$

Table 2.6 Structural damping (to DIN 1055-4 [12] F.5 (2))
$\delta_s = a_1 \cdot n_1 + b_1 \geq \delta_{min}$
where
n_1 = fundamental flexural vibration frequency [Hz].
Parameters a_1, b_1, δ_{min} to 1055-4 [12] Table F.2 (extract)

Type of structure	a_1	b_1	δ_{min}
Reinforced concrete towers	0.050	0	0.025
Masonry/concrete chimneys	0.075	0	0.030