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Probability of exceeding the serviceability limit of antenna masts

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Abstract. With respect to serviceability, antenna masts should be designed so that wind-induced motion will not cause unacceptable lack of transmission for broadcasting users and wireless communication. For such antenna masts with directional radio transmission the serviceability limit state is predominantly governed by the tolerable change of the broadcasting angle of the mounted antenna assembly and therefore by the tip distortion of the mast. In this paper it will be shown that refinements of the present state of design of antenna masts are possible by using the statistics of extremes applied to extreme wind situations and by consideration of the statistical and reliability requirements given by the operator such as frequency and return period of passing the serviceability limit.

Key words: towers; masts; antenna structures; ancillaries; directional radio transmission; serviceability limit; full-scale measurements; wind tunnel modeling; wind-induced deformation; gust response; statistics of extremes; frequency of exceeding; design proposals.

1. Introduction

A large number of self-supporting antenna mast structures with heights of about 30 to 60 m similar to the tested prototypes need to be erected in the future according to the requirements of

- global expansion of mobile phone networks,
- increasing capacities and transmission output,
- development and condensation of regions with low infrastructure,
- new operators entering the market.

Usually the design at serviceability limit state SLS is governed by a limitation of deformations whereas the steel property, plate thickness and prestress forces are used to meet the ultimate limit state design requirements. At present different types of construction are customary. Conical masts of centrifugally cast concrete compete with latticed and sometimes solid steel towers.

Object of this research was to evaluate the probability and the frequency of exceeding the permissible broadcasting angle of antenna masts with directional radio transmission (limiting value $\Delta\varphi = 0{,}5^{o}$) due to static and dynamic wind forces affecting the SLS for different types of design (Kammel and Langer and Rennert and Sedlacek and Ruscheweyh 1997 and 1999). The research was divided into two parts. On one hand long-term full-scale measurements were conducted at a number of prototype structures in cooperation with the IMA in Dresden in continuation of full-scale tests at several steel

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stacks (Langer and Ruscheweyh and Verwiebe 1996). The second part of investigation was undertaken at the atmospheric boundary layer wind tunnel of the Institute of Steel Construction in Aachen using model specimens consisting of composite material with varying inclination for the experimental evaluation of the structural response to wind action. Besides, a comparison of the relevant codes and calculation methods regarding serviceability and reliability requirements by way of calculation was carried out. Concerning this subject only a few other references are established by documentary evidence including results of experimental setups using section models or numerical analysis of full-scale measurements (e.g., Gusella and Spinelli 1989, Holmes and Banks and Roberts 1993, Zeng and Chen and Sun 1996).

2. Long-term full-scale measurement

At five different prototype structures (1× cast concrete, 1× solid steel, 1× bolted lattice with angular cross-section elements and 2× welded/bolted lattice with tubular cross-section elements), see Table 1, strain at the bottom, wind speed and wind direction were monitored continuously for about one year. The prototype structures were mounted with different types of discrete ancillaries such as dish reflectors of varying diameters or rod antennas and other ancillary items e.g., ladders, platforms, see Fig. 1.

To obtain the total duration of crossing a specific deformation level it is necessary to count the frequency of all measured extreme strain events and assign each event to a proper time interval. For that purpose all strain data is recorded in sets of 10,24 seconds at a sampling rate of 0,01 s and the numbers of strain extrema during each data set are counted. In some cases there is only one extremum during a data set, but sometimes there are several extrema. Approximately, the occurrence of each extreme strain event is then rated for time by division of the 10,24-seconds-period by the number of extrema within the data set. These time-rated strain events are assigned to the actual gust wind speed and the section of wind direction (10,24 sec. mean wind) for classification. Hence, the cumulated duration of occurrence for each strain/wind-speed-class can be obtained by addition of the time intervals of all time-rated strain events within the relevant class.

Fig. 2 shows the frequency distribution of wind action depending on the wind direction and the distribution of mean strain in relation to the angle of incidence of the wind at the prototype

Table 1 Structural specifications and dimensions of prototype structures

	Brossen	Schmalbach	Pulsnitz	Nossen	Königsbrück
Type of construction	Steel lattice, with horizontal bracing	Steel lattice	Steel lattice, with secondary bracing	Solid steel	Solid cast concrete, steel top
Members	solid rod	solid rod	angle	-	-
Height [m]	40	40	46,5	40	48,9
No. of panels	4	4	8	3	3+1
Base dimension [mm]	2500× 2500	1800× 1800	4700× 4700	ϕ 1740	ϕ 1596
Top dimension [mm]	1300× 1300	1000× 1000	1100× 1100	ϕ 700	ϕ 828
Natural frequency [Hz]	1,40	1,13	1,47	0,98	0,60
Log. damping decrement [-]	0,035	0,029	0,041	0,042	0,07(1. mode) 0,04(2. mode)

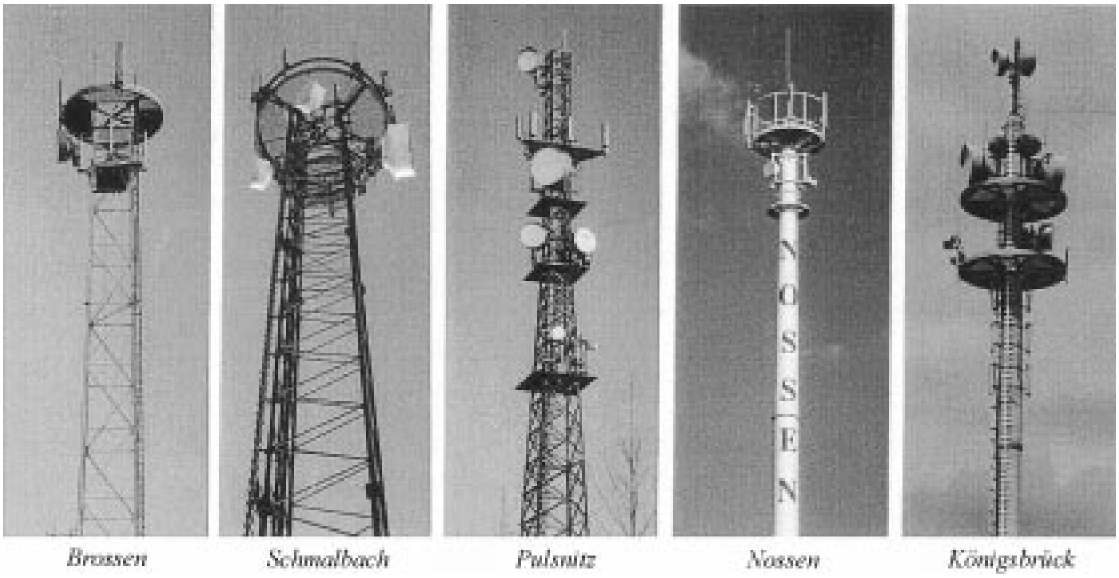

Fig. 1 Antenna mast prototypes

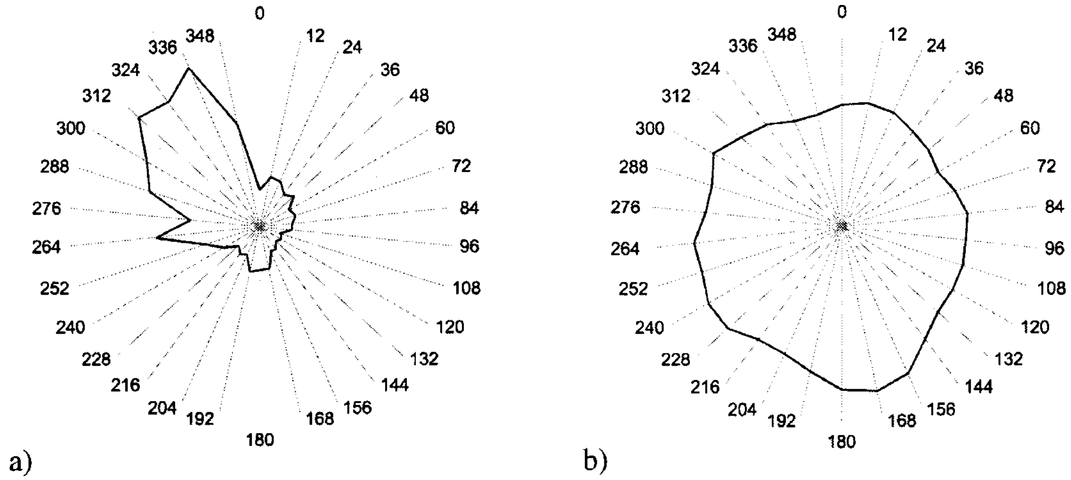

Fig. 2 (a) Frequency distribution of angles of incidence [°] of the wind at the prototype Königsbrück
(b) Mean strain distribution in relation to the angle of incidence [°] at the prototype Königsbrück

Königsbrück schematically.

The reason for the unevenness of the mean strain values in relation to the angle of incidence, see Fig. 2(b), is the antenna assembly. Depending on the angle of incidence the projected area of antennas and drag coefficients are varying. The “0”-direction given in Fig. 2 represents the northern direction. Fig. 3(e) shows the corresponding antenna assembly in ground plan.

The 3D diagrams given in Fig. 4(a) to (d) illustrate the magnitude of strain $|\varepsilon|$ and the added time intervals of time-rated strain events $h(\varepsilon)$ in logarithmic scale related to the actual gust wind speed v_{wind}. At higher wind speeds the curves seem to be cut off, but carrying out an appropriate

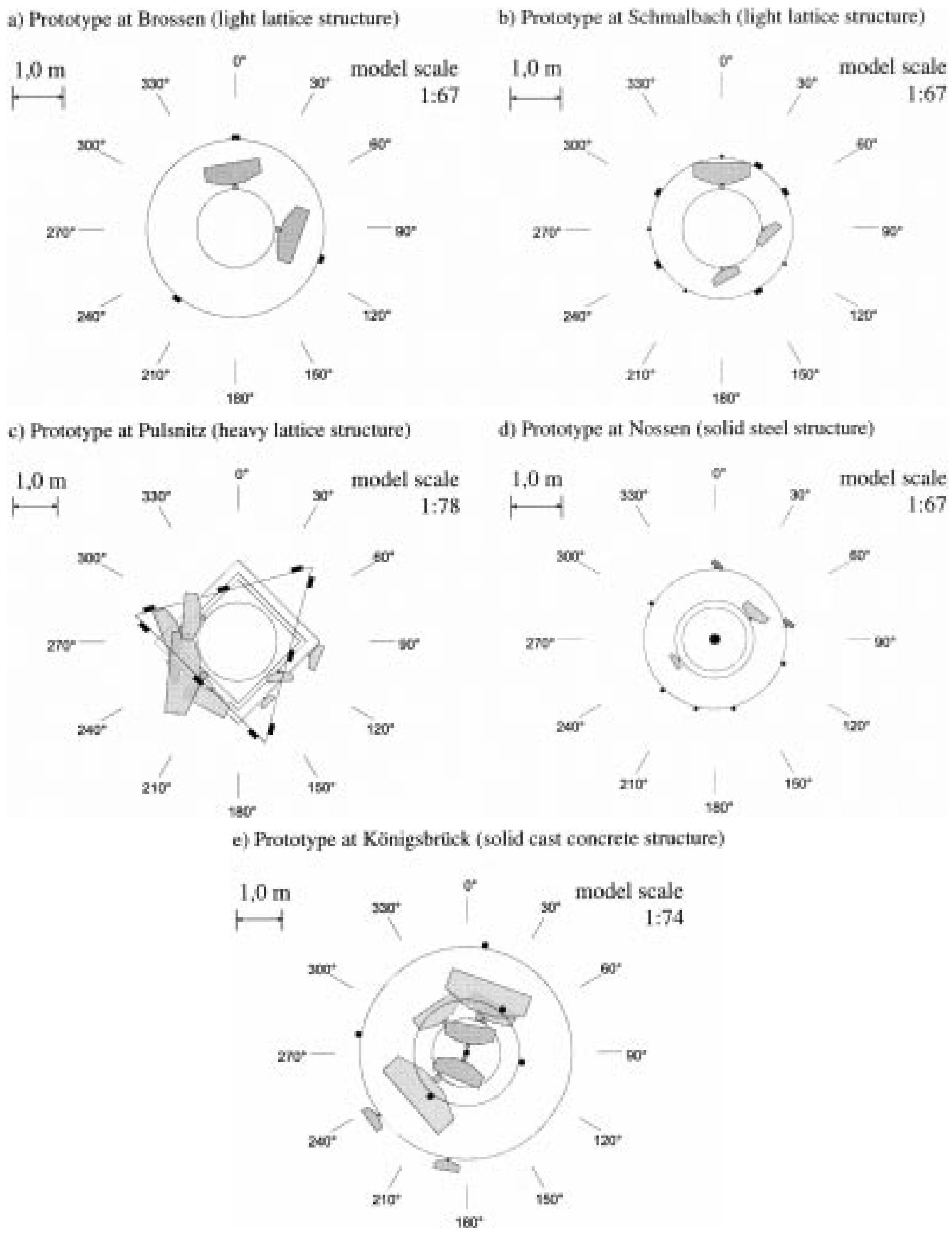

Fig. 3 Schematic ground plan of the model specimens and antenna assemblies (different scales)

projection by extending the curves provides access to the strain values at the extreme wind speed.

The two solid type mast structures, at Nossen (solid steel structure) and Königsbrück (solid cast

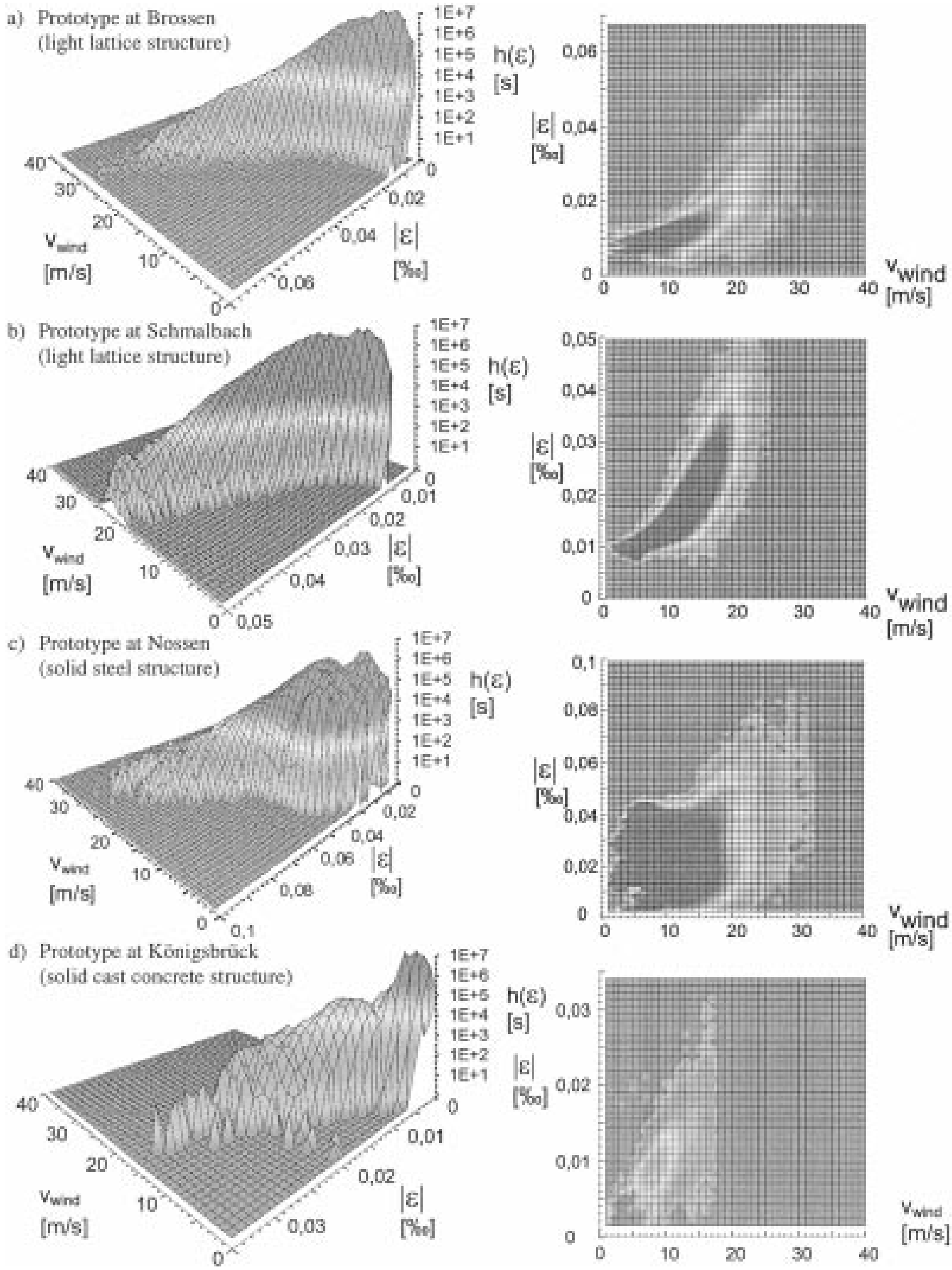

Fig. 4 Added time intervals of all measured time-rated strain events in relation to strain/wind-speed-classes

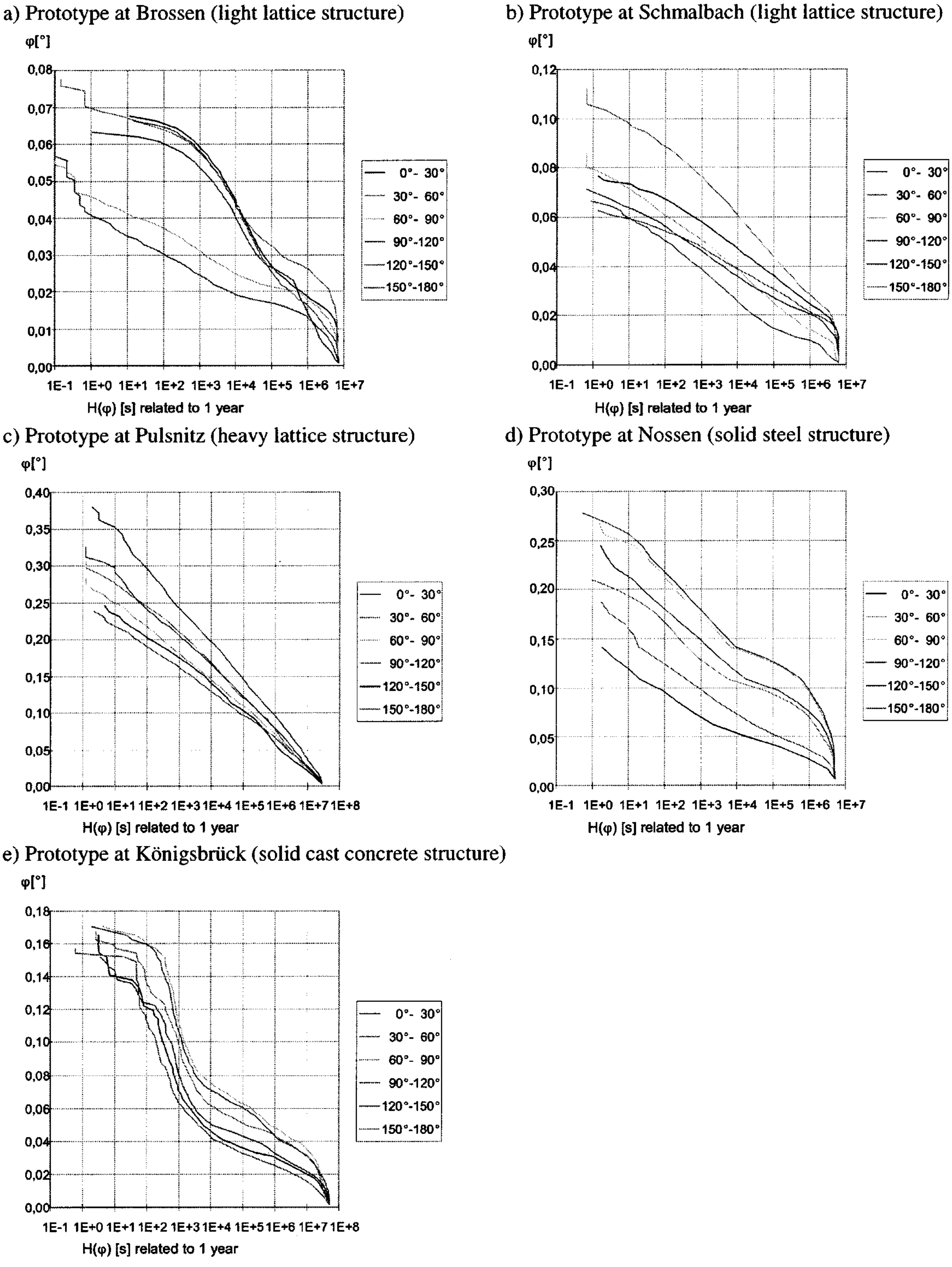

Fig. 5 Cumulative duration of occurrence $H(\varphi)$ of measured tip distortion angles φ [°]

concrete structure), show an increase of deflections in a special range of lower wind speed. This represents the effect of crosswind vibration around the critical wind speed. Remarkably, the range of wind speed with increased vibration amplitudes is widened because of vortex shedding in different heights and in consequence with different excitation frequencies. However, the deflections due to crosswind vibration are far smaller than due to alongwind action caused by gusty wind in both cases, especially if projected up to the extreme gust wind speed of $v \approx 42$ m/s (according to DIN 4131 (DIN 1991) and DIN 4228 (DIN 1989), wind zone II, at a height of 40 m, for the 5 sec. mean wind).

The tip distortion angles φ [^{o}] are then determined by conversion of the measured strain values at the mast basis considering the relevant vibration mode shape. The cumulative frequencies $H(\varphi)$ of tip distortion angles are rated for time representing the events as duration of occurrence in seconds in the same way as it has been done for the strain values and classified in sectors of wind direction and related to the actual wind speed, as described above. As result of about one year of full-scale measurement the cumulative duration of occurrence of tip distortion angles $H(\varphi)$ are shown in Fig. 5(a) to (e) in logarithmic scale for all of the five prototype structures.

High values of tip distortion angles are reached only for particular wind directions and very short periods. At low values of tip distortion angles or strain, respectively, the number of events is limited due to signal filtering. Due to the limited duration of the full-scale measurements it is necessary to project the strain and deflection data up to the relevant design gust wind speed corresponding to a 50 year return period.

3. Wind tunnel tests

A comprehensive study of multiple arrangements of antenna installation has been carried out in a boundary layer wind tunnel by measuring acceleration and strain in perpendicular orientation, see Fig. 6 and Fig. 3(a) to (e). For the experimental setup particular attention has been paid to provide adequate spectral and turbulence characteristics. Three different conical model specimens with constant angle of inclination (0,13^o, 0,35^o and 0,66^o) combined with several antenna assemblies and ancillaries were tested at different wind speeds (up to 30 m/s) and angles of wind incidence (in sections of 30^o).

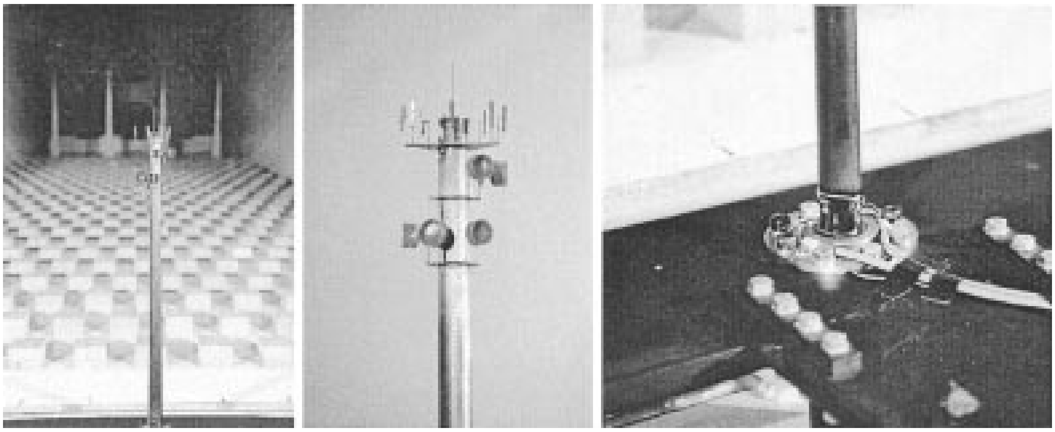

Fig. 6 Carbon fibre reinforced plastic model specimen with strain gauges in the boundary layer wind tunnel

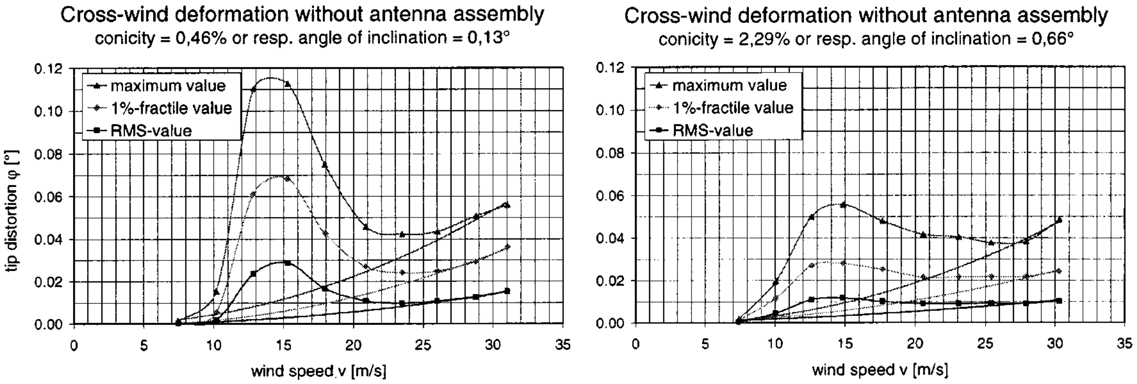

Fig. 7 Result diagrams for two of the model structures concerning cross-wind vibration amplitudes (the subsidiary lines indicate the superelevation of tip distortion as against lateral alongwind response)

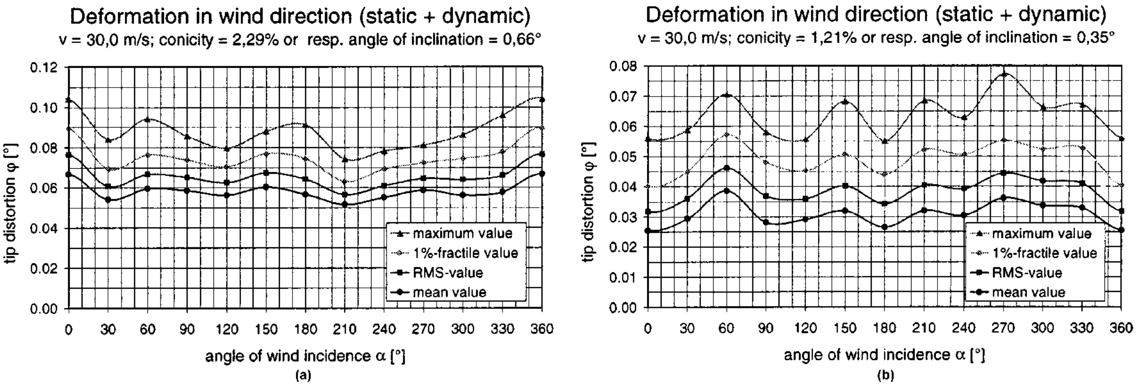

Fig. 8 (a) Result diagram for one of the Königsbrück prototype models (b) Result diagram for one of the Pulsnitz prototype models

The crosswind vibration amplitudes measured at the model structures are smaller than expected due to calculation, especially for large angles of inclination or clustered antenna assembly. The reduction of tip distortion or crosswind vibration amplitudes, respectively, with increasing inclination is illustrated by Fig. 7. The results indicate that the antenna assembly and mainly the conical shape of the structure provide a considerable reduction of the correlation length of vortex separation in any case. This effect has been observed at the two solid prototype structures Nossen (angle of inclination $0{,}74^{o}$) and Königsbrück (angle of inclination $0{,}51^{o}$), too, see Fig. 4(c) and (d), but is neglected in the relevant codes, although scientific findings concerning this subject have been obtained many years ago (Quadflieg 1975).

Further results concerning the magnitude of deflections in gusty wind were obtained from measurements in the boundary layer wind tunnel according to interference and blockage effects of the antenna assembly depending on the arrangement of antennas at the mast and the wind direction and speed, see Fig. 8 as example of results. For the given antenna assemblies and angles of wind incidence see Fig. 3.

4. Relevant codes

Some inadequacies in the relevant codes become evident by a critical view of the design assumptions. Essential are the following aspects:

(1) Wind drag follows by multiplication of wind pressure q (5 sec. mean), drag coefficient c_f, projected area A_{ref} with due consideration to the solidity ratio and the gust response factor Φ_B. The presently used design requirement for the serviceability limit state (partial safety factor $\gamma = 1{,}0$) for antenna mast structures with directional radio transmission in Germany is based on the arbitrary assumption of half wind pressure neglecting gust response having a mean return period of 50 years. The calculation of the tip distortion at half wind pressure neglecting the gust response factor follows from Eq. (1):

$$\varphi_{SLS} = \frac{\varphi_{ULS}}{2 \cdot \Phi_B} < 0,5^{\circ} \tag{1}$$

where : φ_{SLS} = tip distortion at serviceability limit state;
φ_{ULS} = tip distortion at ultimate limit state;
Φ_B = gust response factor (using ENV 1991-2-4, Annex B (Eurocode 1995), the dynamic factor c_d comprises gust response by way of spectral analysis)

The limiting value of deflection $\Delta\varphi = 0{,}5^{\circ}$ is based on another arbitrary assumption. Both assumptions have been laid down by the former German Federal Postal Administration (Bundespost-ZTV 1986) and do not seem advisable and consequently are in need of improvement. On the other hand, ENV 1993-3-1 (Eurocode 1997) contains detailed serviceability limit requirements only with respect to cross-wind vibration amplitudes.

(2) ENV 1991-2-4 (Eurocode 1995) allows for considering the effect of wind direction (direction factor c_{DIR}) at design state. This opportunity of reducing wind loads without breaking the safety level is not used in Germany. This point is of particular interest for antenna masts with directional radio transmission because of the dependency of wind direction for drag coefficients and projected area. A simple addition of wind drag of all discrete ancillary items with their maximum wind drag neglecting varying wind direction, interference and blockage effects is usually assumed.

(3) Calculations give a jump in stresses between terrain category II and III. Interpolation or an additional intermediate category are recommended.

(4) Generally structural damping at serviceability limit state is low due to elastic stresses. On the other hand antenna assembly and other ancillary items provide an increase of aerodynamic damping reducing the gust response of the structure.

5. Probability of exceeding

The probability of exceeding F^* is defined by Eq. (2):

$$F^*(y) = 1 - (F(y))^T \tag{2}$$

where : $F(y)$ = cumulated frequency distribution, e.g., following Gumbel or Weibull
T = reference period

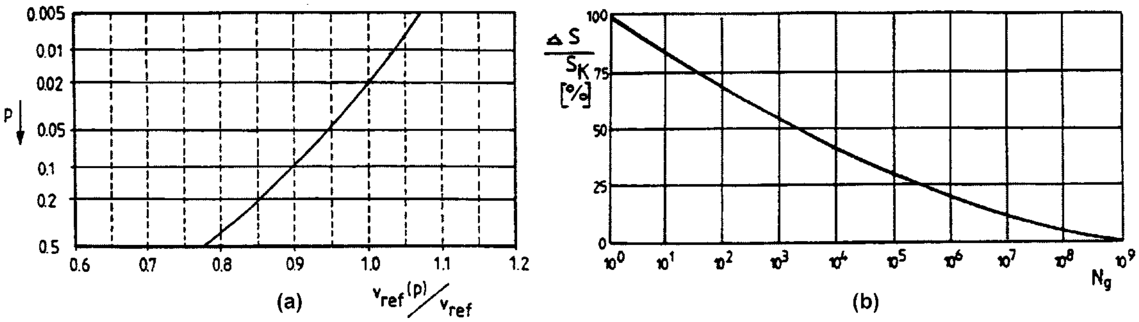

Fig. 9 (a) Reference velocity with an annual probability of exceeding of p (b) Number of gust loads N_g for an effect $\Delta S / S_k$ during a 50 years return period

Based on Gumbel's frequency distribution (e.g., Gumbel 1958, Kasperski 1992) the reference wind velocity $v_{ref}(p)$ for annual probability of exceeding p is specified in ENV 1991-2-4, 7.3 (Eurocode 1995), see Eq. (3) and Fig. 9(a).

$$v_{ref}(p) = v_{ref} \cdot \left(\frac{1 - K_1 \cdot \ln[-\ln(1-p)]}{1 - K_1 \cdot \ln[-\ln 0{,}98]} \right)^n \tag{3}$$

For effects of the wind which are proportional to the wind velocity special advice is available (Solari 1993). In the same way ENV 1991-2-4, Annex B.6 (Eurocode 1995) gives advice for evaluating the number of loads for gust response, N_g, where the values ΔS of an effect of the wind are reached or exceeded during a period of 50 years. ΔS is expressed in % of the characteristic value S_k of the effect having a 50 years return period, i.e., having an annual probability of exceeding of $p = 0{,}02$. For that a Weibull distribution is used, see Fig. 9(b).

As the tip distortion angle φ is approximately proportional to the wind pressure due to alongwind response, the ratio of effects $\Delta S / S_k$ needs to be squared to obtain a diagram, or a table, respectively, which illustrates the relationship between return period, ratio of wind effects and frequency of exceeding, see Fig. 10 and Table 2. Then $\Delta\varphi / \varphi_k = 100\%$ may be taken as reference value which is exceeded once in a 50 years period.

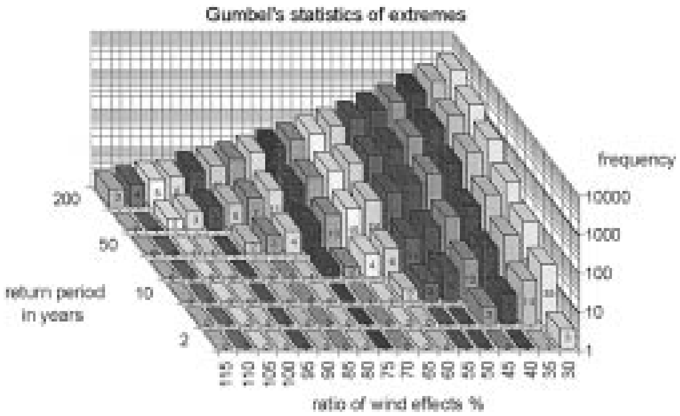

Fig. 10 Frequency of exceeding following Gumbel's statistics of extremes

Table 2 Frequency of exceeding during return period T due to a ratio of effects which is proportional to the wind pressure e.g., $\Delta\varphi / \varphi_k$ [%] based on an equal level of probability

		Return period T [year]				
		100	**50**	20	10	2
Ratio of wind effects : this is a value proportional to the wind pressure, or in particular to the tip distortion angle $\Delta\varphi / \varphi_k$ in %	115	1	0	0	0	0
	110	1	0	0	0	0
	105	2	1	0	0	0
	100	3	**1**	0	0	0
	95	4	1	0	0	0
	90	5	2	0	0	0
	85	7	3	1	0	0
	80	11	4	1	0	0
	75	16	6	2	0	0
	70	24	10	2	1	0
	65	36	15	4	1	0
	60	57	24	6	2	0
	55	92	40	11	3	0
	50	152	68	19	6	0
	45	262	119	35	12	0
	40	470	**221**	68	23	0
	35	891	432	140	50	1
	30	1804	904	309	116	3

Considering an appropriate gust response factor, e.g., $\Phi_B \approx 1{,}25$, based on the 5 second mean wind velocity, for antenna structures then the customary design requirement of half wind pressure neglecting gust response, thus $\Delta\varphi / \varphi_k = 100\% / (2 \cdot 1{,}25) = 40\%$, results in a number of 221 events of exceeding during a period of 50 years, or based on equal probabilities, respectively, not more than 1 event in 2 years. The level of probability is equivalent to that for exceeding the maximum value (100%) assuming full wind pressure once in a period of 50 years, see Table 2.

Hence, calculations were conducted according to DIN 4131 (1991) and DIN 4228 (1989). The gust response factors Φ_B [–] for all prototypes are within a range from 1,12 to 1,28 and thus the ratio of tip distortion at SLS to tip distortion at ULS is between 39% and 44%. Taking this value the frequency of exceeding the serviceability limit of $\Delta\varphi = 0{,}5^{\circ}$ during a reference period of 50 years can be evaluated, referring to Table 2.

Table 3 contains the measured maximum deflections and the corresponding wind speed as well as the projected deformation at design wind speed, and enables for a comparison of the performance of all five antenna prototypes using statistics of extremes. All measured deflections projected to the calculated maximum wind speed ($v \approx 42{,}0$ m/s) φ_{proj} as well as the frequency of exceeding the permissible tip distortion of $\Delta\varphi = 0{,}5^{\circ}$ during a 50 years period are smaller than calculated in accordance with DIN 4131 (1991) and DIN 4228 (1989). Consequently the present design is conservative.

Table 3 Summary of measured and calculated data

		Brossen	Schmalbach	Pulsnitz	Nossen	Königsbrück
Maximum tip distortion φ_{means} [^{o}]		0,07^o	0,11^o	0,38^o	0,28^o	0,17^o
Measured at wind speed v[m/s]		33	26	33	32	19
Distortion projected to calc. max. wind speed ($v \approx 42{,}0$ m/s) φ_{proj} [^{o}]		0,12^o	0,29^o	0,62^o	0,52^o	0,83^o
Maximum calculated tip distortion according to DIN (ULS) φ_{ULS} [^{o}]		0,26^o	0,58^o	0,72^o	0,74^o	1,20^o
Calculated tip distortion at half wind pressure neglecting gust response acc. to DIN (SLS) φ_{SLS} [^{o}]		0,12^o	0,25^o	0,32^o	0,32^o	0,47^o
Frequency of exceeding a distortion of 0,50^o during a period of 50 years	calculated according to DIN	0	3	10	12	179
	meas. and projected to max. wind speed	0	0	4	1	24

6. Conclusions

The full-scale measurements as well as the wind tunnel tests prove that the application of currently used design methods generally provide a conservative design. Measured stresses and deformations remain under the calculated ones, particularly at light lattice structures. Structures with multiple antenna installation lead to a more conservative design than structures with few antenna installation. Any additional antenna provides a lower increase of total wind drag due to increasing interference effects and decreasing projected areas.

Based on the results of this investigation a design method is proposed taking into account the statistical characteristics of extreme wind situations. Hence, serviceability requirements will be satisfied depending on the permitted frequency of exceeding given by the operator. As conclusion, the following recommendations for an economical design of masts, where the antenna accuracy governs the serviceability limit, regardless, whether concrete or steel and solid or lattice can be stated:

(1) Definition of the desired service life corresponding to the return period by the operator, e.g., a 50 years period. At the same level of probability a reduction of design service life, e.g., to 20 years, results in a significant reduction of frequency of exceeding and a more economical design.
(2) Definition of the tolerable number of events of exceeding during service life by the operator.
(3) Replacing the presently used design requirement for SLS of half wind pressure neglecting gust response by calculating the maximum tip distortion at full wind pressure including gust response. The calculation of deflections should be carried out for the relevant wind direction with due consideration to a detailed addition of wind loads acting on each antenna.
(4) The frequency of exceeding during the selected reference period may then be taken from Table 2 after calculating the ratio of $\Delta\varphi = 0{,}5^o$ to the maximum tip distortion φ determined

according to (3), or for the particular case of a 50 years period using Annex B.6 of ENV 1991-2-4 (Eurocode 1995), respectively, see Fig. 9(b). The probability of exceeding should provide a safety level equal to exceeding of the maximum deflection once during the return period.

(5) The safety assessment for serviceability limit state may then be satisfied by comparison of calculated and permissible frequency of exceeding.

This method generally provides a reduction of dynamic wind loads. Further advantage can be taken by raising the permissible number or duration of passage failure or by reducing the reference period for service or the level of probability, respectively, according to the operator’s request. In some cases this enables for subsequent supplementary installation of antennas at existing masts, provided that the basic design requirements for the ultimate limit state are not violated.

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