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SELECTED ISSUES OF AERODYNAMICS OF STEEL CHIMNEYS

WYBRANE ZAGADNIENIA AERODYNAMIKI KOMINÓW STALOWYCH

A b s t r a c t

This paper presents general principles of managing the reliability of steel chimneys according to Eurocodes EN 1990 and EN 1993-3-2. It discusses the basis for static calculations and dimensioning and compares Eurocode guidelines to the requirements of old Polish Standards. The use of standard procedures is illustrated by an example of static calculations and dimensioning of a steel chimney shell.

Keywords: *static calculations of steel chimney*

S t r e s z c z e n i e

W artykule przedstawiono ogólne zasady zarządzania niezawodnością kominów stalowych wg Eurokodów EN 1990 i EN 1993-3-2. Omówiono podstawy ich obliczeń statycznych i wymiarowania, a także porównano wytyczne Eurokodu z wymaganiami stawianymi przez stare polskie normy. Sposób wykorzystania procedur normowych zilustrowano przykładem liczbowym obliczeń statycznych i wymiarowania powłoki komina stalowego.

Słowa kluczowe: *obliczenia statyczne kominów stalowych*

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1. Introduction

This article presents an analysis of the reliability of a steel chimney according to the principles of Eurocode EN 1993-3-2 [1]. The standard applies to vertical steel chimneys of a circular or conical cross-section. Possible solutions include cantilevered (in lattice or self-bearing towers) and guyed chimneys. The article introduces general principles of managing the reliability of steel chimneys according to old standards and Eurocodes, it compares loads under old standards and Eurocodes as well as presenting the basis for their calculation and dimensioning in a deteriorated condition. Moreover, it describes a comparative analysis of static calculations of chimneys according to old Polish Standards and Eurocodes

2. Elements of the reliability analysis

The European Standards (Eurocodes) introduced a few years ago contain requirements that are different from old Polish Standards in terms of static and strength calculations of steel chimneys. The main change is the implementation of reliability management by defining the reliability class of a chimney. This depends on the consequences to society, environment and economy of the destruction of a chimney. Depending on the reliability class, the standard requires various values of partial coefficient γ_F to static and dynamic loads. Their differentiation has a great impact on the calculation procedure carried out according to the Eurocode guidelines.

Eurocodes require a comparison of the design values: the bearing capacity R_d and the load effect E_d. According to the recommendations included in EN 1990 [2] regarding the basics of structure design, the ultimate limit state condition can be expressed as a scalar one-parameter bearing capacity R and the related impact effect E as follows:

$$E_d = E(F_{d1},...a_{d1},...\theta_{d1},...) \leq R(X_{d1},...a_{d1},...\theta_{d1},...) \tag{1}$$

where:

index $_d$ refers to the design values,
F_{di} – impact on the structure,
X_{di} – mechanical properties of the structure's material,
a_{di} – geometric properties of the structure,
θ_{di} – uncertainty parameters of the calculation model.

According to the Eurocodes, the method for testing reliability does not usually necessitate that the design values x_d be substituted into the ultimate limit state equation. Instead, the equation is substituted with so-called representative values X_{rep} and F_{rep}, which can be:

- characteristic values, i.e. quantiles of loads – F_k, material strength – ηX_k, and geometric properties – a_d (where η is the conversion factor);
- nominal values (central values of geometric properties a_{nom}).

The design values F_d and X_d are determined by multiplying or dividing the representative values by relevant partial coefficients:

$$F_d = F_{\text{rep}}\gamma_F \rightarrow E_d = E(F_{\text{rep}}\gamma_F) \tag{2}$$

$$X_d = \eta X_{\text{rep}} / \gamma_M \rightarrow R_d = R(\eta X_{\text{rep}} / \gamma_M) \tag{3}$$

Partial coefficients γ_F in formula (3) and γ_{M} in formula (4) account for random variation of impacts, material strength and modelling error of the random variables, and can be presented as the following products:

$$\gamma_F = \gamma_f \gamma_{Sd} \quad \gamma_M = \gamma_m \gamma_{Rd} \tag{4}$$

The numeric values of load factors γ_F specified in Eurocode EN 1990 are presented as three sets, depending on the analysed ultimate limit state. Technically, the specifications are secure for all objects and buildings. However, partial coefficients y_F for impacts on chimneys are additionally specified in EN 1993-3-2 as an alternative for the recommendations included in Eurocode EN 1990. The differentiation of chimneys in terms of their reliability class is presented in Table 1.

Table 1

Reliability differentiation for chimneys [1]

Reliability class	Definition
3	Chimneys erected in strategic locations, such as nuclear power plants or in densely populated urban locations. Major chimneys in manned industrial sites where the economic and social consequences of their failure would be very high.
2	A11 normal chimneys at industrial sites or other locations that cannot be defined as Class 1 or Class 3.
1	Chimneys built in open countryside whose failure would not cause injury. Chimneys less than 16m high in unmanned sites.

Partial factors for material property γ_M are specified in [1, 3, 4] as follows:
- γ_{M0} = 1.00 – resistance of structural elements or members related to the yield strength f_y, where no global or local buckling occurs;
- γ_{M1} = 1.10 – resistance of structural elements or members related to the yield strength f_y, where global or local buckling is considered;
- γ_{M2} = 1.25 – resistance of structural elements or members related to the ultimate tensile strength f_u, resistance of bolts and welds;
- γ_{M3} = 1.25 – slip resistance of preloaded bolts at ultimate limit state;
- $\gamma_{M3,\text{ser}}$ = 1.10 – slip resistance of preloaded bolts at serviceability limit state;
- γ_{M6} = 1.10 – fatigue resistance of shell;
- γ_{Ff} = 1.00 – partial factor for the fatigue loading;
- γ_{Mf} – partial factor for the fatigue strength, depending on the selected fatigue assessment method.

Coefficient values depending on the reliability class are juxtaposed in Table 2.

Table 2

Partial factors for actions γ_F [1]

Type of Effect	Reliability class	Permanent Actions	Variable Actions
Unfavourable	1	1.2	1.6
	2	1.1	1.4
	3	1.0	1.2
Favourable	All classes	1.0	0.0
Accidental situations		1.0	1.0

3. Comparison of old and new standards

Steel chimneys are designed according to the provisions specified in standard [1]. Its requirements contain references to standards [3–5]. Those calculations are different from the guidelines of old Polish Standards [6, 7] in terms of load values and the analysed conditions. Table 3 presents a juxtaposition of various loads and environmental impact according to the old and new standards.

Table 3

Load outlines

Load	PN B 03201	EN 1993-3-2
Dead load	Considered	Considered
Technological loads	Considered	Considered
Load during execution	Considered	Considered
Dust and ashes	Omitted	Considered
Imperfections	Only if second-order effects are necessary	Always accounted for
Snow loads	May be omitted	May be omitted
Atmospheric icing	May be omitted	Accounted for
Wind action; pressure	Accounted for	Accounted for
Wind action; vortex	A simplified and detailed procedure (alternative)	A simplified and detailed procedure (alternative)
Wind action; galloping	Accounted for	Accounted for
Wind action; interference	Accounted for	Accounted for
Gas internal pressure	Omitted	Accounted for
Gas temperature	Only for guyed chimneys if the core temperature exceeds 50°C	Accounted for

Gas temperature; impact on mechanical properties of steel	If over 70°C, reduction of fatigue strength	Reference to standard [8]
Gas temperature; checking the possibility of the formation of condensate (corrosion)	Accounted for	Reference to standard [8]
Outside temperature	Only for guyed chimneys if the core temperature exceeds 50°C	Always accounted for
Temperature impact on steel creep	Omitted	If the core temperature exceeds 400°C
Inner fire	Omitted	Accounted for
Chemical; corrosion	Include the impact of thickness change (corrosion allowance)	Include the impact of thickness change (corrosion allowance)
Chemical; change of mechanical properties of steel	Decreased design strength of steel	Reference to standard [8]
Seismic and paraseismic impact	Accounted for	Reference to standard [8] and [9]
Mining terrain deformation	Accounted for	Reference to standard [8] and [9]
Ground settlement	Accounted for	Reference to standard [2], [8] and [9]

The comparison of loads that need to be accounted for in the design of chimneys shows that the Eurocode requires a deeper consideration of loads that have an impact on the chimney. Impacts that could be omitted in some cases (such as imperfections or icing) are now obligatory to analyse. There are also conditions that were previously unaccounted for (fire inside the chimney, material creep or a clearly stated obligation to consider the impact of dust and ashes).

The article includes a detailed analysis of the guidelines regarding the values of technological load and wind pressure.

Standard [1] establishes slightly different requirements regarding technological load as compared to [6]. A comparison of recommended values according to both standards is presented in Table 4.

The old Polish Standards were not consistent in terms of wind load. Although there was a standard defining wind load [10], in case of many tower type buildings there were separate regulations (for example [6, 10, 11–14]) that significantly changed the wind load profile. A comparison of these standards is presented in [15].

According to the provisions of standard [10], wind load is defined in the following way:

$$p = \gamma_f q_k C_e C \beta \quad (5)$$

where:

- γ_f – partial wind load coefficient;
- q_k – characteristic value of the wind velocity pressure, depending on the structure location in the country;
- C_e – wind exposure factor describing vertical wind profile depending on the terrain category;
- C – aerodynamic drag coefficient depending on the structural shape;
- β – gust response factor depending on the structure dynamic properties.

T a b l e 4

Comparison of technological load values

Load	PN B 03201	EN 1993-3-2
Imposed loads on platforms: (vertical)	2.0 kN/m^2 alternatively 3.0 kN	2.0 kN/m^2
On railings: (horizontal)	0.3 kN/m	0.5 kN/m
On ladders (vertical)	1.0 kN	No guidelines

The relationship between wind speed and altitude (coefficient C_e) can be presented as a polygonal curve. Chimneys should be regarded as structures prone to the dynamic impact of wind, thus it is necessary to precisely calculate the value of coefficient β. The minimum value is 1.8.

Standard [6] introduces changes to the wind load formula. According to the provisions of the standard, wind load is calculated in the following way:

$$p = \gamma_f q_k c_{te} c_e c_s n \beta \tag{6}$$

where:

- γ_f – partial wind load coefficient;
- q_k – characteristic value of the wind velocity pressure depending on the structure location in the country (value consistent with standard [10]);
- C_{te} – coefficient accounting for the scheduled chimney lifetime;
- C_e – wind exposure factor (equivalent of C_e in standard [10], yet calculated differently);
- C_s – aerodynamic drag coefficient (equivalent of C in standard [10], yet with a different value);
- β – gust response factor depending on the structure dynamic properties (calculated according to the recommendations of standard [10], yet with slight changes to parts of the formulae);
- n – number of flues in one structure not covered by a external shell.

According to the guidelines of Eurocode [16] defining the wind load, in the case of chimneys, it should be calculated in the following way:

$$p = \gamma_f q_b c_e c_f c_s c_d \tag{7}$$

where:

- γ_f – partial wind load coefficient;

q_b – characteristic value of the wind velocity pressure depending on the structure location in the country, accounting for seasonal changes and the influence of prevailing winds (equivalent of q_k in Polish Standards);
c_f – aerodynamic drag coefficient (equivalent of C in standard [10]);
$c_s c_d$ – structural coefficient describing possible interactions of structural vibrations and turbulent wind effects (similar to β in standard [10]).

Figure 1 presents a comparison of wind load values in the function of chimney height. This includes a dimensionless parameter describing the load defined as:

$$w = 10^6 p / f_y \tag{8}$$

where:
- w – dimensionless parameter of wind load;
- p – wind pressure [Pa] calculated according to the guidelines in standards [6], [10] and [16], calculated according to formulas (5–7);
- f_y – yield strength of steel.

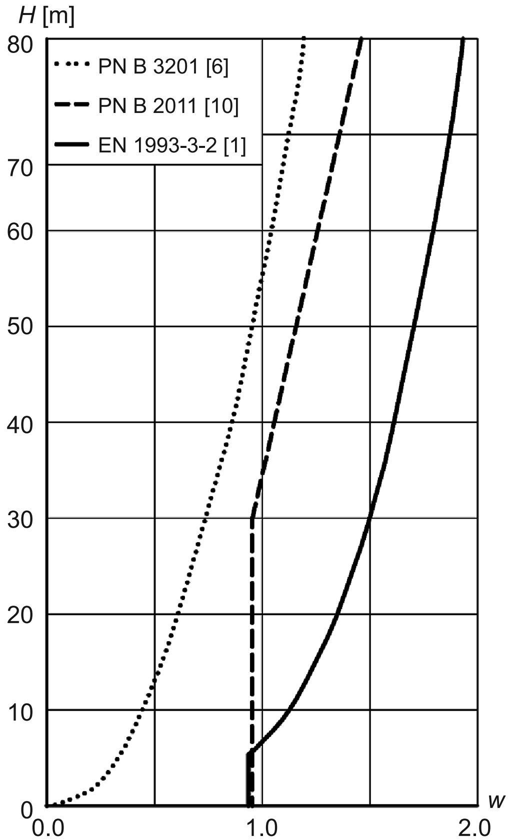

Fig. 1. Comparison of wind load according to various standards

The comparison was based on the following assumptions:
- climatic zone 1 of wind load
- industrial area, i.e. surrounding type *C* according to [10] and 4 according to [16],
- chimney diameter 4.0 m.

A significant change compared to previous standards is the need to account for structural imperfection. In the case of free-standing cantilever chimneys, this is treated as top deflection with the following value:

$$\Delta = (h/500)\sqrt{(1+50/h)} \tag{9}$$

where:

h – chimney height (depending on the location of the symbol in the formula, its measurement unit is [m] or it is a dimensionless value).

4. Calculation example

A comparison of guidelines from the new and old standards was conducted for an 80 meters high cylindrical steel chimney. Originally, the chimney was located in Kraków Łęg Power Station [18]. The structure is presented in Fig. 2.

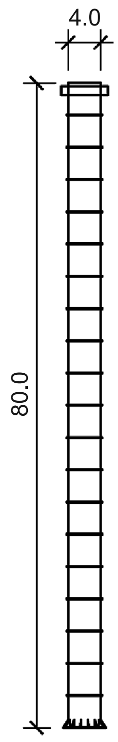

Fig. 2. The chimney

The calculation of the chimney was based on the following data and conditions:
- diameter D = 4 000 mm, height H = 80 000 mm;
- temperature impact on chimney operation and vortex load was omitted;
- location – Kraków;
- steel grade 1.4016 (H17);
- mechanical parameters – yield strength f_y = 240 MPa, fatigue limit f_u = 430 Mpa.

The chimney bearing structure is a cylindrical sheet metal shell. The assembly member is 4.00 m long. Conduits are connected with one another by flanged contact screws. The sheet metal core is 10–20 mm thick. The chimney was modelled (as the chimney in the Kraków Łęg Power Station in Cracow) with a variable shell thickness of 8–12 mm.

Safety factors were derived from EN standards. Calculations were based on EN standards. They used reliability class 2 and production class B. Additionally, a beam model was analysed according to the guidelines on standard [1].

Two models of structure were taken into consideration: a shell model and a bar model.

The chimney was modelled as a shell structure loaded with a dead load, a technological load, wind pressure and wind suction. The impact of imperfections was also considered in terms of concentrated force applied to the chimney top. It was established that the force value results in equivalent movement of the chimney top according to [1]. The values of wind pressure and suction were applied according to [16]. The distribution of pressure around the perimeter was aligned with the guidelines of standard [16]. The wind load coefficient for the beam structure with a circular section was assumed as 0.7.

The impact of flanges connecting conduits and the technological bridge on the shell stiffness was also accounted for. The initial calculations do not include the impact of the thermal effects of hot gases and the dynamic effects related to the wind load. The calculations were carried out in Algor software. Linear elastic analysis was used (LA according to [5]).

According to [17], the section class for elements with a circular section should be calculated as a ratio of diameter to wall thickness, which in the case of the analysed structure results in section class 4. As specified in [17], in such a case, the calculation process should be in line with [5]. With this chimney section, class 3 is possible only if 44 mm thick sheet steel is used, which is economically unreasonable.

In the beam model, wind pressure bending interacts with vertical forces buckling (dead load, technological load). Additionally, second-order effects should be accounted for by applying strict conditions to the condition of pure buckling and the increase of the bending moment value at the bottom of the cantilever.

In the case of the shell model, the chimney is calculated according to the requirements of standard [1]. This requires that in the bearing ultimate limit state, the following conditions are checked:
- static equilibrium;
- strength of its structural elements (i.e. plastic limit state = SL1 according to [5] and tensile resistance);
- overall stability;
- local buckling of its elements (limit state SL3 according to [5]);
- fatigue of its structural elements, including low-cycle fatigue (limit state SL4 according to [5]);

– failure of connections (bolted and welded joints).
– In the serviceability limit state, the evaluation is based on:
– deformations or deflections in the along wind direction and/or in the cross-wind direction which adversely affect the appearance or effective use the structure;
– vibrations, oscillations or sway which may cause alarm among bystanders;
– deformations, deflections, vibrations, oscillations or sway which may cause damage to non-structural elements.

Checking conditions LS1, LS3 and LS4 according to standard [5] involves checking the following conditions:

$$\sqrt{[\sigma_{x,Ed}^2 + \sigma_{\theta,Ed}^2 - \sigma_{x,Ed}\,\sigma_{\theta,Ed} + 3(\tau_{x\theta,Ed}^2 + \tau_{xn,Ed}^2 + \tau_{\theta n,Ed}^2)]} / f_{eq,Rd} \le 1.0 \tag{10}$$

$$(\sigma_{x,Ed}/\sigma_{x,Rd})^{kx} - k_j(\sigma_{x,Ed}/\sigma_{x,Rd})(\sigma_{\theta,Ed}/\sigma_{\theta,Rd}) + (\sigma_{\theta,Ed}/\sigma_{\theta,Rd})^{k\theta} + (\tau_{\theta,Ed}/\tau_{\theta,Rd})^{k\tau} \le 1.0 \tag{11}$$

$$\Delta\sigma_E \gamma_{Ff} < \Delta\sigma_R / \gamma_{Mf} \tag{12}$$

where:

$\sigma_{i,Ed}$ – meridional, circumferential or shearing stress;
k_i – local stability factors;
$\sigma_{i,Rd}$ – critical stress at loss of stability;
$\Delta\sigma_E$ – variable stress at fatigue;
$\Delta\sigma_R$ – fatigue strength of notches according to standards [1] and [4].

5. Conclusions

The results of the beam model were analysed, including second-order effects. Results of shell model were analysed too. They were related to the actual chimney in the Kraków Łęg Power Station. The analysis results are presented in Table 5.

Table 5

Calculation results

Model, maximum shell thickness	Maximum effort		Sway/acceptable sway
	LS1	LS3	
Beam, 10 mm	0.692		0.375
Shell, 12 mm	0.378	4.108	0.178
Shell, 20 mm	0.222	0.762	0.112

The calculation results show that the conditions that were the most difficult to be met are connected with shell stability. Meeting the requirements regarding stability is only possible if the wall thickness reaches 10 mm in the upper part and 20 mm in the lower part, this results in an almost two-times increase of thickness as compared to the initial structure (8–12 mm).

Eurocode provisions are stricter than the old Polish Standards. Loads and actions from dust and ashes, imperfections, atmospheric icing, gas internal pressure, gas temperature, outside temperature, temperature impact on steel creep and inner fire must be always taken into account, this is contrary to the old Polish Standards. The effects of this requirement are higher intensities of actions applied to the structure in the calculation process. The same, static action of wind has a larger value in the case of calculations according to Eurocode than with the old Polish Standards. According to there results, contemporary structures are more massive than older.

A few phenomena: the impact of gas temperature on corrosion and on the mechanical properties of steel, the impact of aggressive gases on the mechanical properties on steel, seismic effects, paraseismic effects, terrain deformation and ground settlement effects must be analysed according to few additional standards. The comparison between old and contemporary requirements is possible after more accurate analysis.

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