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EXAMPLES OF DESIGNING STEEL SHELL STRUCTURES ACCORDING TO EUROCODES

PRZYKŁADY PROJEKTOWANIA STALOWYCH KONSTRUKCJI POWŁOKOWYCH WEDŁUG EUROKODÓW

A b s t r a c t

The paper presents an analysis of the guidelines of the European standards on procedures for the calculation of shell structures. The analysis is illustrated with examples concerning three types of structures of the type i.e.: a chimney, a silo and a tank.

Keywords: *steel structures*, *shell structures*, *chimney*, *silo*, *tank*

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

W artykule przedstawiono analizę wytycznych norm europejskich dotyczących procedur obliczeniowych konstrukcji powłokowych. Analiza zilustrowana została przykładami obliczeniowymi dotyczącymi trzech konstrukcji, czyli komina, silosu i zbiornika.

Słowa kluczowe: *konstrukcje metalowe*, *konstrukcje powłokowe*, *komin*, *silos*, *zbiornik*

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1. Introduction

The chosen design examples of steel structures set up in the paper are all shells of revolution. That is why they should be designed according to the rules given in the standard PN-EN 1993-1-6 [1]. They belong however to three various types of buildings for which detailed regulations were also elaborated separately: for chimneys in the regulation PN-EN 1993-3-2 [2], silos in the regulation PN-EN 1993-4-1 [3] and tanks in PN-EN 1993-4-2 [4].

Before 2010 each of the three types of steel structures was designed according to the adequate object standard in the Polish project practice, ie chimneys – PN-93/B 03201 [5], silos for loose materials PN-B-03202: 1996 [6], cylindrical vertical tanks PN-B-03210: 1997 [7]. To each type of the structure corresponding Polish comprehensive monographs have been dedicated – for instance [8] and [9] for chimneys, [10] for silos and [11] for tanks.

The way in which wind actions on structures are estimated can be an illustration of differences between calculations for the three types of shells after "old" Polish and "new" European standards. Silos and tanks were calculated according to [12], chimneys according to [5]. The results of calculations according to different standards for a few cases of tower-type structures are presented in detail in [13]. For example, Fig. 1 shows

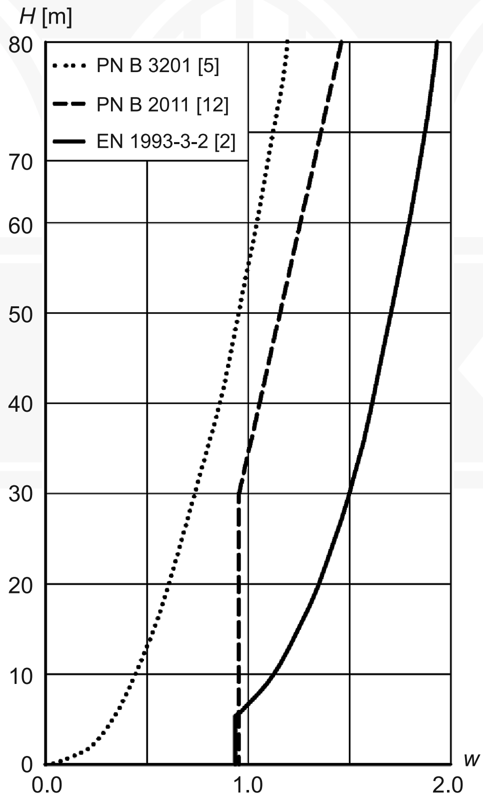

Fig. 1. Comparison of wind load according to various standards

a comparison of wind load values as a function of the chimney height H. This includes a dimensionless parameter describing wind action defined as:

$$w = 10^6 \, p / f \tag{1}$$

where:

- w – dimensionless parameter of wind load,
- p – wind pressure [Pa] calculated according to the guidelines in standards [12] and [14],
- f – yield strength of steel.

The above described comparison was based on the following assumptions:

– climatic zone 1 of wind load according to [12] and [14],
– industrial area, i.e. type C of the surroundings according to [12] and 3 according to [14],
– 4.0 m diameter of the structure.

The most essential change in comparison to the traditional "old" approach to the design procedures of the considered shell structures is the integration of the rules within the range of their strength and stability check as well as the uniform approach to their reliability. The latter is described in the standard [15]. The uniform approach to all the shell structures is also shown in standard [1] and described in the commentary to it [16, 17]. This uniform approach is based on the two most important rules:

1. Common approach to each structure according to EN 1990 [15];
2. Wide range of MES application to the calculation of shell structures.

The algorithm of calculations is presented in Table 1.

Table 1

Algorithm of calculations

Step of analysis	Number of Eurocode	Comments
1	EN 1990	General information on reliability of structures
2	EN 1991-1, EN 1991-4	Loads and actions
3	EN 1993-3-2, EN 1993-4-1, EN 1993-4-2	Specific requirements for chimneys, silos and tanks
4	EN 1993-1-6	Calculation of shell structures
5	other	Calculation of other parts of structures

2. Reliability of structures

Analyses of reliability should be performed according to the standards [2–4, 15] and [18]. For chimneys, the most important parameter is the reliability class (RC), for tanks it is a consequence class (CC). Two parameters must be taken into account for silos, i.e. an action assessment class (AAC) and a consequence class (CC). These classes are very important for the values of safety factors of actions and sets of their combinations (for chimneys and silos) and serviceability limit states (for chimneys), for the choice of method of structural analysis (for tanks and silos). The method of classifying structures as well as the results of the qualifications are presented in Tables 2–9 for different shell structures.

Table 2

Reliability differentiation for chimneys [2]

Reliability class	Definition
1	Chimneys built in open countryside whose failure would not cause injury. Chimneys less than 16 m high in unmanned sites.
2	All normal chimneys at industrial sites or other locations that cannot be defined as class 1 or class 3.
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.

Table 3

Partial factors for permanent and variable actions [2] (for chimneys)

Type of effects	Reliability class	Permanent actions	Variable actions
unfavourable	1	1.0	1.2
	2	1.1	1.4
	3	1.2	1.6
favourable	1, 2, 3	1.0	0.0
Accidental situations		1.0	1.0

Table 4

Recommendations for maximum amplitudes of cross-wind vibrations [2] (for chimneys)

Reliability class	Limits to cross-wind vibration amplitude
1	0.15 D
2	0.10 D
3	0.05 D

where:
D – outer diameter.

Table 5

Reliability differentiation for tanks [4]

Reliability class	Definition
1	Agricultural tanks and tanks containing water.
2	Medium sized tanks with flammable or water-polluting liquids located in urban areas.
3	Tanks storing liquids or liquefied gases with toxic or explosive potential and large tanks with flammable or water-polluting liquids located in urban areas.

Table 6

Methods of analysis for tanks [4]

Consequence class	Circular shell tank structure	Rectangular box tank structure
1	Membrane theory with simplified formulas to describe local bending effects	Static equilibrium for membrane forces and beam theory for bending
2	Membrane theory with bending theory or numerical analysis (FEM)	An analysis based on linear plate bending and stretching theory
3	Numerical analysis (FEM)	An analysis based on nonlinear plate bending and stretching theory

Table 7

Reliability differentiation for actions in silos [18]

Action assessment class	Definition
1	Silos with a capacity below 100 tons.
2	All silos covered by standard [18] and not placed class in 1 or 3.
3	Silos with a capacity in excess of 10 000 tons or silos with a capacity in excess of 1000 tons in which any of the following design situations occur: a) eccentric discharge with $e_0/d_c > 0.25$ b) squat silos with top surface eccentricity with $e_t/d_c > 0.25$

Generally, for the higher number of action assessment class, the higher values of actions are used. Additionally, more complicated cases of combinations of actions must be analysed.

Table 8

Reliability differentiation for silos [3]

Consequence class	Definition
1	Silos with capacity between 10 and 100 tons.
2	All silos covered by standard [3] and not placed in class 1 or 3.
3	Ground supported silos or silos supported on a complete skirt extending to the ground with capacity in excess of 5000 tons or discretely supported silos with capacity in excess of 1000 tons or silos with capacity in excess of 200 tons in which any of the following design situations occur: a) eccentric discharge b) local patch loading b) unsymmetrical filling

Table 9

Methods of analysis for silos [3]

Consequence class	Circular shell silos structure	Rectangular box silos structure
1	Membrane theory with simplified formulas to describe local bending effects	Static equilibrium for membrane forces and beam theory for bending
2	Membrane theory with bending theory or numerical analysis (FEM)	An analysis based on linear plate bending and stretching theory
3	Numerical analysis (FEM)	An analysis based on nonlinear plate bending and stretching theory

3. Shell structures in general

Standard [1] defines four basic limit states for steel shell structures and shows the methods that should be used in order to determine the values of stresses and cross-sectional forces in the given state according to the pattern outlined in Table 10.

Table 10

Methods (models) of analysis for each limit states of shells [1]

Limit state (name)	Method (model) of analysis
LS1 (plastic limit state)	Linear elastic analysis (LA), materially nonlinear analysis (MNA), geometrically and materially nonlinear analysis (GMNA)
LS2 (cyclic plasticity limit state)	Analysis LA or GNA, materially nonlinear analysis MNA or GMNA
LS3 (buckling limit state)	Analysis LA, linear elastic bifurcation analysis (LBA), materially nonlinear analysis MNA, geometrically and materially nonlinear analysis with imperfections GMNIA
LS4 (fatigue limit state)	Analysis LA or GNA with coefficients of stress concentration

In the above mentioned standards conditions for dimensioning the shell are specified in accordance with the used method of analysis for the chosen limit state. For instance, in the state LS1 (plastic limit) the following condition should be fulfilled:

$$\sigma_{Ed} \leq f_{yk} / \gamma_{m0} \tag{2}$$

where:

- σ_{Ed} – design value of a component of stress tensor or equivalent stress,
- f_{yk} – characteristic value of yield strength,
- $\gamma_{M0} = 1.0$,

while in the state LS3:

$$\sigma_{Ed} \leq \chi f_{yk} / \gamma_{m1} \tag{3}$$

where:

χ – coefficient of instability.

$\gamma_{M1} = 1.0$.

Acceptable types of analysis for shell structures are presented in detail in Table 11.

Table 11

Types of analysis for shell structures [1]

Types of analysis	Deformations	$\sigma \leftrightarrow \varepsilon$	Imperfections
Linear elastic shell analysis (LA)	Small	Linear	No
Linear elastic bifurcation analysis (LBA)	Small	Linear	No
Geometrically nonlinear elastic analysis (GNA)	Large	Linear	No
Materially nonlinear analysis (MNA)	Small	Nonlinear	No
Geometrically and materially nonlinear analysis (GMNA)	Large	Nonlinear	No
Geometrically nonlinear elastic analysis with imperfections included (GNIA)	Large	Linear	Yes
Geometrically and materially nonlinear analysis with imperfections included (GMNIA)	Large	Nonlinear	Yes

The choice of the appropriate calculation method for a given type of structure is made in accordance with the corresponding standard for silos and tanks with respect to the consequence class which in turn depends on the geometry of the structure and the conditions of its exploitation [3, 4]. In the case of chimneys [2], the method of analysis depends on the class of cross-section. Here, for classes 1–3 the shell is considered to be like a generalised beam with bending effects and possibly taking the II-range effects into account, whereas cross-sections of class 4 are treated like shells with use of a linear analysis LA.

4. Design examples of shell structures

Three structures are presented here for example: a steel chimney [19], a silo [20], a tank [21]. Views of structures and the results of FEM static analysis for these structures are presented in the tables and figures below. These were recommended to be published in full in [19].

Table 12

Characteristics of analysed structures

Structure	Consequence class	Thickness [mm]	Grade of steel	FEM shell elements
Chimney in an electric power station	CC2	10–20	1.4401 stainless steel	Four-nodes
Silo constructed from flat sheets	CC2	6–12	S355	Four-nodes
Tank for storage of ammonia water	CC3	6	1.4301 stainless steel	Four-nodes

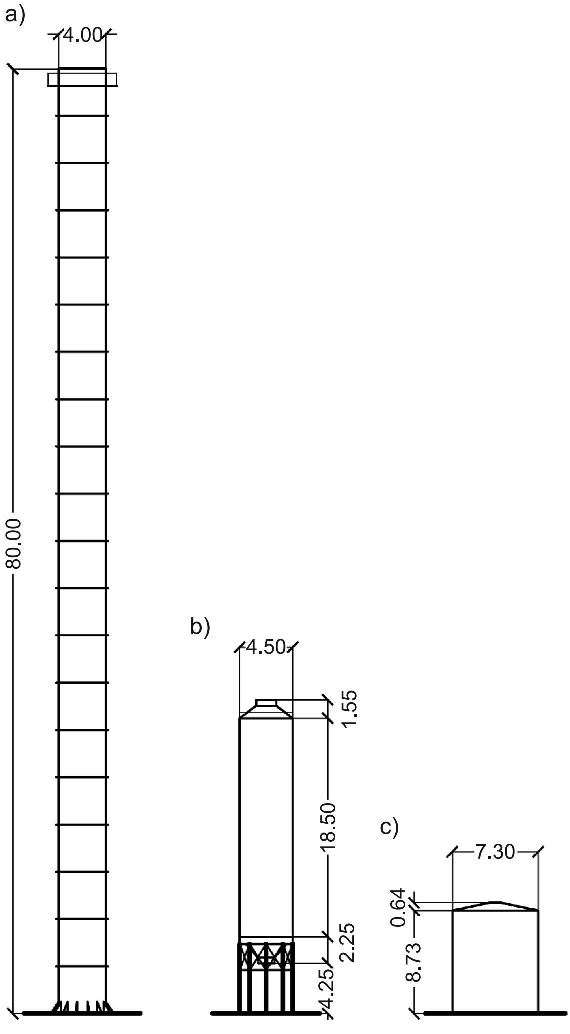

Fig. 2. Schemes of analysed structures: a) chimney, b) silo, c) tank

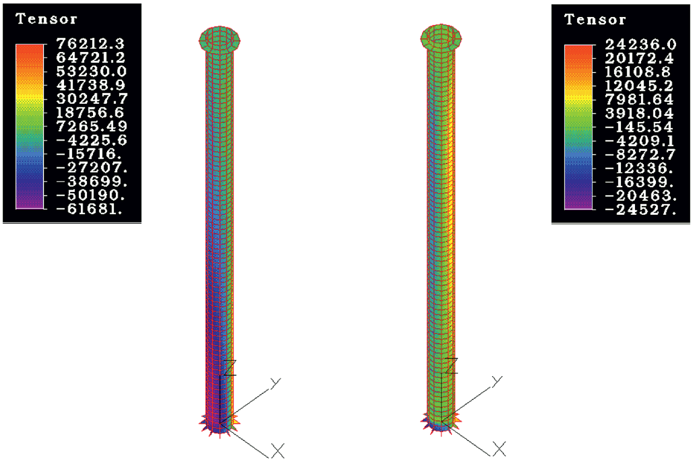

Fig. 3. Example design results for the chimney 80m high chimney for the pressure of wind velocity: σ_{HMH} [kPa], meridional stresses (left), circumferential stresses (right), LA analysis, (Algor [22])

Table 13

Results FEM for chimney

Limit state (condition)	Check
LS1 (1)	0.220 < 1.0
LS3 (2)	0.760 < 1.0

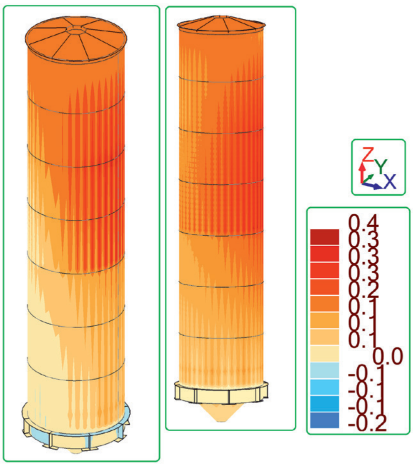

Fig. 4. Silo for wheat, FEM results, displacements u_x (left), general displacements (right) [cm], LA analysis, (Robot [23])

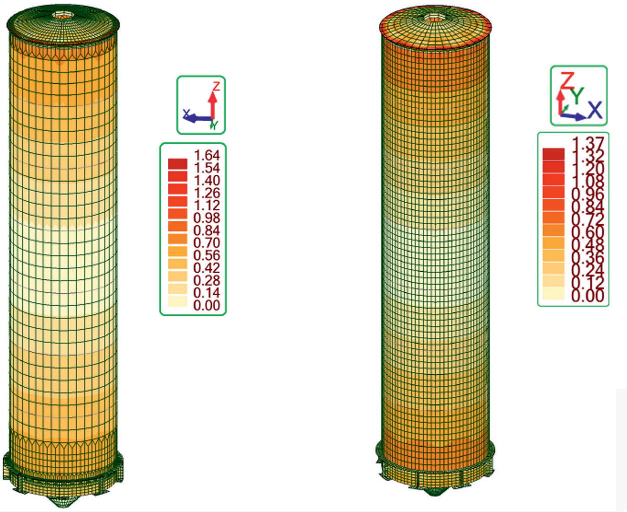

Fig. 5. Comparison of results from LA analysis (left)and GMNA analysis (rigth); dead weight, σ_{HMH} [MPa]

Table 14

Results FEM for silo

Limit state (condition)	Check
LS1 (1)	0.277 <1.0
LS3 (2)	0.907 < 1.0

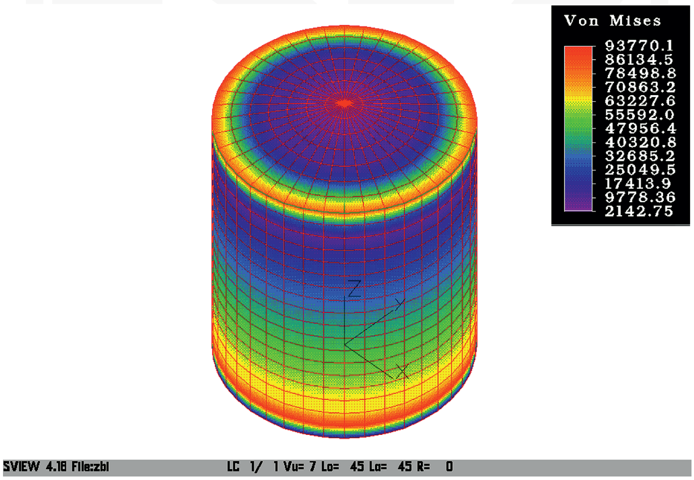

Fig. 6. Results of calculations (Algor [22]) for the most disadvantageous equivalent stress, LA analysis, [kPa]

Table 15

Results FEM for tank

Limit state (condition)	Check
LS1 (1)	$0.723 < 1.0$
LS3 (2)	$0.095 < 1.0$

Safety factors: for ammonia water $\gamma_F = 1.40$, other live loads $\gamma_F = 1.50$, for dead weight $\gamma_F = 1.35$, $\gamma_{M0} = 1.10$, $\gamma_{M2} = \gamma_{M5} = 1.25$, $\gamma_R = 1.05$, $k_{Fi} = 1.10$ (factor for actions for RC3).

5. Summary

The three design examples of special steel structures constructed from sheets with the cross-sections which are shells of revolution are presented. A uniform approach to assessing the reliability of the structures was adopted. The wind load was calculated according to Eurocode [14] in order that it provides the largest values for all the different standards. In all cases, the FEM as well as the algorithm described in standard [1] were effectively used for the analysis of the stress state (effort) and displacements of the shells.

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