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# A COMPARATIVE STUDY OF ALONG-WIND AND CROSSWIND RESPONSES OF STEEL CHIMNEYS ACCORDING TO POLISH AND EUROCODE STANDARDS

# STUDIA PORÓWNAWCZE PODŁUŻNEJ I POPRZECZNEJ ODPOWIEDZI KOMINÓW STALOWYCH NA ODDZIAŁYWANIE WIATRU PRZYJĘTE WEDŁUG NORM POLSKICH I EUROKODU

## Abstract

An analysis of the response of steel chimneys to wind action is presented in this paper. The approaches presented in the Polish standards and in Eurocode 1 referring to steel chimneys and wind action are shown here. Comparisons of along-wind and crosswind action according to these procedures are made. Responses to the wind action, i.e. displacements of the top of each chimney, are compared. Real chimneys were analyzed. In almost every case, significant vibrations due to vortex excitation was observed. Structural data was obtained from the literature. All chimneys and wind actions were modelled in FEM system – Autodesk Mechanical Simulation 2013. Very significant differences of the crosswind response were observed when analyzing two approaches proposed by Eurocode. Lateral displacements were larger than longitudinal displacements in many analyzed cases.

*Keywords: steel chimneys, wind action, vortex excitation, wind standards*

## Streszczenie

Przedmiotem analiz przedstawionych w niniejszym artykule jest odpowiedź kominów stalowych na oddziaływanie wiatru, którą wyznaczono na podstawie wytycznych zawartych w Normach Polskich oraz w Eurokodzie 1. Analizowano dwa rodzaje odpowiedzi: wzdłuż średniego kierunku wiatru oraz w kierunku prostopadłym. Odpowiedź konstrukcji wyrażono za pomocą przemieszczenia wierzchołka, któro dla różnych kominów ze sobą porównano. Analizom poddano rzeczywiste kominy stalowe, dla których na przestrzeni lat zaobserwowano znaczące wzbudzenie wirowe. Dane konstrukcyjne określono na podstawie literatury. Wszystkie konstrukcje oraz oddziaływanie wiatru zostały zamodelowane w programie MES – Autodesk Mechanical Simulation 2013. Otrzymano znaczne różnice odpowiedzi poprzecznej kominów, gdy obciążenie przyjmowano zgodnie z dwoma procedurami Eurokodu. Przemieszczenia poprzeczne są w wielu przypadkach większe niż podłużne.

*Słowa kluczowe: kominy stalowe, oddziaływanie wiatru, wzbudzenie wirowe, normy wiatrowe*

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## 1. Introduction

When analyzing wind action on steel chimneys, two directions should be considered: along-wind action and crosswind action. Crosswind action is generated by Benard-Kármán vortices. Estimation of the first one in almost all standards over the world is based on the mathematical model elaborated by Alan Davenport in the 1960s, [1–2]. Eurocode 1 [3] allows determination on the basis of the peak values of wind speed, while Polish standards, PN-93/B-03201 [4] and PN-77/B-02011 [5], are based on 10-minute mean wind speeds. Crosswind action, according to Eurocode 1 [3], can be calculated with the use of two alternative procedures originally based on the Ruscheweyh model – procedure 1, [6–9] and Vickery-Clark model – procedure 2, [10–13]. These procedures lead to considerably different results. In Polish standard PN-93/B-03201 [4] the simplified model proposed by Ruscheweyh was introduced. A vortex excitation phenomenon, lateral vibrations, lock-in effect as well as analyses of different standard approaches describing vibrations of industrial chimneys which are generated with vortices have been widely presented in literature [12–15] and more recently in [16–41].

In this paper, along-wind action and crosswind action are separately analyzed for three types of steel chimneys: type 1 – of constant outer diameter; type 2 – with tapered lower part; type 3 – tapered for the whole height of the structure. Finite element models of each chimney structure were made on the basis of the data obtained from literature. The objective of this paper is a comparative study of the along-wind and crosswind responses of three groups of steel chimneys according to approaches presented in Polish and Eurocode standards.

## 2. Wind action according to Polish and Eurocode standards

### 2.1. Along-wind action

In Polish standards, PN-93/B-03201 [4] and PN-77/B-02011 [5] the static along-wind action equivalent to the dynamic one is calculated in pressure units according to the formula:

$$p_x = q_k C_e C_x C_{te} \beta \tag{1}$$

where: $q_k$ – characteristic wind speed pressure, $C_e$ – exposure factor, $C_x$ – aerodynamic drag coefficient, $C_{te}$ – coefficient regarding expected service time, $\beta$ – dynamic wind gust coefficient.

According to Eurocode 1 [3] wind force acting on the structure is calculated from:

$$F_w = c_s c_d \cdot c_f \cdot q_p \left(z_e\right) A_{ref} \tag{2}$$

where: $c_s c_d$ – structural factor, calculated for the reference height $z_s = 0.6H$ and being the product of $c_s$ – size factor reducing wind action as the result of a lower correlation due to large structure dimensions and $c_d$ – dynamic factor increasing wind action regarding gusts, $c_f$ – aerodynamic drag coefficient, $q_p(z_e)$ – peak wind speed pressure at the height of the analyzed structure section, $A_{ref}$ – reference area exposed to wind action.

### 2.2. Crosswind action

Polish standard, PN-93/B-03201 [4] gives two procedures: simplified with wind action treated as static equivalent to the real dynamic one, and detailed procedure with dynamic wind action as a harmonic one in accordance with the natural frequency of the structure. In both procedures, wind action should be applied in the area of extreme structure deflections, at a correlation length of $0.25H$, not less than $6D$ ($H$ – structure height, $D$ – diameter). Simplified procedures may only be applied for the first natural frequency, when the slenderness $H/D < 30$, Scruton number Sc < 15, and expected service time is less than 20 years. The load is expressed in [kN/m] and calculated with the formula:

$$p_y = \frac{0,05\rho}{T_1^2 \delta_s} c_{lat} D^3 \tag{3}$$

where: $\rho$ – air density, $T_1$ – first period of natural vibrations, $\delta_s$ – logarithmic decrement of structural damping, $c_{lat}$ – aerodynamic lift force coefficient.

According to the detailed procedure, dynamic wind action referring to the $i$-th mode shape is calculated with the use of the following formula:

$$p_{y,i} = \frac{\rho v_{kr,i}^2}{2} D c_{lat,i} \sin\left(\omega_i t\right) \tag{4}$$

where: $\omega_i$ – $i$-th circular frequency of natural vibrations, $v_{kr,i}$ – $i$-th critical wind speed, $v_{kr,i} = f_i \cdot D/\mathrm{St}$, $f_i$ – $i$-th natural frequency, St – Strouhal number.

Eurocode 1 [3] allows the application of two procedures for calculation of crosswind action. Both of them are based on the evaluation of the maximum deflections generated by vortex excitation. Wind action considering internal forces is applied in accordance with the mode shape and is calculated for $j$-th node of the structure according to the formula:

$$F_{i,j} = m_j \left(2\pi n_i\right)^2 \Phi_{i,y,j}\left(z\right) \max y_F \tag{5}$$

where: $m_j$ – the vibrating mass at the node $j$, $n_i$ – natural frequency referring to the $i$-th mode shape, $\Phi_{i,y,j}(z)$ – normalized $i$-th mode shape in the crosswind direction, max $y_F$ – maximum displacement caused by vortex excitation.

The first of the procedures has been elaborated by Ruscheweyh [6–9] and takes resonant vortex excitation into account. The basics of the second procedure have been proposed by Vickery [10–11], then modified by Dyrbye and Hansen [12–13] by introducing the influence of turbulence and in this form introduced into Eurocode 1 [3]. The basis of both procedures is the determination of maximum displacements caused by vortex excitation (max $y_F$).

In Ruscheweyh's procedure, the effective vortex excitation is assumed as uniformly distributed along the effective correlation length $L_j$. The increase in crosswind action caused by lock-in phenomenon is taken into account by feedback between correlation length $L_j$ and amplitude of lateral vibrations $y_F$. The ratio of correlation length to outer diameter of the chimney $L_j/D$ depends on the ratio of the vibration amplitude to the outer diameter in the following way: when $y_F/D < 0.1$ then $L_j/D = 6.0$, when $0.1 < y_F/D < 0.6$ then $L_j/D = 4.8 + 12y_F/D$, when $y_F/D > 0.6$ then $L_j/D = 12$. The maximum vibrations amplitude is calculated from the equation:

$$\frac{\max y_F}{D} = K_W K c_{lat} \frac{1}{\mathrm{St}^2} \frac{1}{\mathrm{Sc}} \tag{6}$$

where: $D$ – outer diameter of the chimney, $K_w$ – coefficient of effective correlation length, $K$ – coefficient of the mode shape, $c_{lat}$ – coefficient of aerodynamic lift, St – Strouhal number, Sc – Scruton number.

Maximum amplitude max $y_F$ must be calculated with use of iterative procedure. One should assume the initial displacement $y_f$, then calculate $L_j$, then $c_{lat}$ and $K_w$ (which also depends on $L_j$) and $K$, finally, estimate max $y_F$ according to the equation (6). If max $y_F$ is different from initial value the procedure must be repeated.

Maximum displacement in the second procedure is calculated from the equation:

$$y_{\max} = \sigma_y \cdot k_p \tag{7}$$

where: $\sigma_y$ – standard deviation of displacements at the location of maximum deflection, $k_p$ – peak factor.

Standard deviation and peak factor are described by the following equations:

$$\frac{\sigma_y}{D} = \frac{1}{\mathrm{St}^2} \cdot \frac{C_c}{\sqrt{\frac{\mathrm{Sc}}{4\pi} - K_a \cdot \left[1 - \left(\frac{\sigma_y}{D a_L}\right)^2\right]}} \cdot \sqrt{\frac{\rho D^2}{m_e}} \cdot \sqrt{\frac{D}{H}} \tag{8}$$

$$k_p = \sqrt{2}\left\{1 + 1.2 \arctan\left[0.75\left(\frac{\mathrm{Sc}}{4\pi K_a}\right)^4\right]\right\} \tag{9}$$

where: $C_c$, $K_a$ – aerodynamic parameters which are dependent on turbulence intensity, Reynolds number, mode shape, mean wind speed and outer diameter changing along the height, $a_L$ – limited amplitude obtained at very low damping, $m_e$ – equivalent mass per unit length.

Value of the peak factor is usually between 3.5 and 4 for low vibration amplitudes and equals to $2^{1/2}$ for high amplitudes.

Crosswind load may not be taken into consideration when: critical wind speed $v_{kr}$ is larger than the 10-minutes mean wind speed at a height of 10 m reduced by time of chimney exploitation or Sc > 15 or this is a guyed chimney or there are dampers on the chimney [4]. According to Eurocode 1 [3], vortex excitation must not be analyzed when critical wind speed is larger than 1.25 of the mean wind speed at respective height.

## 3. Analyzed steel chimneys

Three groups of chimneys were analyzed: 35 chimneys of a constant diameter (type 1); 38 chimneys with a tapered lower part and a constant diameter on the top section (type 2); 9 chimneys tapered on the whole height of the structure (type 3) – detailed data is taken from literature [8–9, 12–15, 18, 23, 29, 33]. Finite element models were prepared for each of the chimneys and modal analysis was performed as the first stage of the study. Structural data are presented for every chimney in Tables 1–3. The basic denotations are presented in Figure 1. Moreover, the following denotations are introduced: $m_e$ – equivalent mass of the chimney; $\delta_s$ – logarithmic decrement of structural damping; $f_1$ – first frequency of natural vibrations; $\lambda = H/D$ ($\lambda = H/D_T$) – chimney slenderness; $m_{e\_\mathrm{calc}}$, $\mathrm{Sc}_{\mathrm{calc}}$, $f_{1\mathrm{calc}}$ $V_{kr,1}$ – equivalent mass; Scruton number; the first frequency; the first critical wind speed obtained by FEM calculations. Exact total mass of the structure is represented in the FEM models, however, natural frequencies obtained in calculations differ from the ones presented in the data in some cases (as is noted in Tables 1–3). This is caused by the lack of sufficiently detailed information about stiffness and mass distribution throughout the height of the structures as well as the service time when frequencies were measured. Taking this into account, an applied numerical approach seems reasonable. Moreover, in some cases, frequencies of vibrations were only very roughly estimated in in-situ conditions with no special equipment.

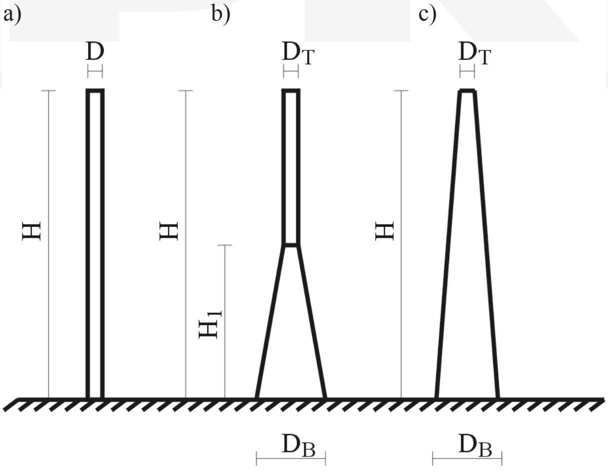

Fig. 1. Denotations of the steel chimneys: a) type 1; b) type 2; c) type 3

Table 1

**Structural data, dynamic and damping parameters for chimneys of type 1**

| Lp | $H$ | $D$ | $m_e$ | $\delta_s$ | $f_1$ | $\lambda$ | $m_{e\_calc}$ | $Sc_{calc}$ | $f_{1calc}$ | $V_{kr,1}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | [m] | [m] | [kg/m] | [-] | [Hz] | [-] | [kg/m] | [-] | [Hz] | [m/s] |
| 1 | 17 | 0.6 | 95 | 0.025 | 2 | 28.33 | 95.3 | 10.6 | 2.227 | 6.7 |
| 2(1) | 23 | 1.5 | 510 | 0.038 | | 15.33 | 511.2 | 13.8 | 2.271 | 17.0 |
| 3 | 25.5 | 1.8 | 360 | 0.031 | | 14.17 | 359.7 | 5.5 | 2.898 | 26.1(3) |
| 4 | 25.5 | 0.71 | 199 | 0.025 | 0.72 | 35.92 | 199.1 | 15.8 | 1.102 | 3.9 |
| 5 | 26 | 1.25 | 199.2 | 0.030 | 1.88 | 20.80 | 199.6 | 6.1 | 1.991 | 12.4 |
| 6 | 28 | 0.914 | 88.8 | 0.015 | 1.72 | 30.63 | 88.8 | 2.6 | 1.872 | 8.6 |
| 7 | 29 | 1.4 | 216 | 0.019 | | 20.71 | 216.9 | 3.4 | 1.687 | 11.8 |
| 8 | 30 | 0.816 | 135.7 | 0.020 | 1.06 | 36.76 | 135.5 | 6.5 | 1.094 | 4.5 |
| 9 | 30 | 0.711 | 157 | 0.025 | 0.7 | 42.19 | 157.0 | 12.4 | 0.848 | 3.0 |
| 10 | 31 | 1.5 | 240 | 0.031 | 1.5 | 20.67 | 242.1 | 5.3 | 1.796 | 13.5 |
| 11 | 31 | 1.35 | 215 | 0.031 | 1.6 | 22.96 | 217.5 | 5.9 | 1.619 | 10.9 |
| 12 | 34 | 0.813 | 159 | 0.025 | 0.76 | 41.82 | 159.1 | 9.6 | 0.761 | 3.1 |
| 13 | 35 | 1.8 | 280 | 0.019 | | 19.44 | 276.2 | 2.6 | 1.763 | 15.9 |
| 14 | 35 | 0.813 | 201.6 | 0.015 | 0.61 | 43.05 | 201.8 | 7.3 | 0.751 | 3.1 |
| 15(1) | 38 | 3.3 | 1080 | 0.031 | | 11.52 | 1085.5 | 4.9 | 1.888 | 31.1(3)(4) |
| 16 | 38 | 1.016 | 231 | 0.030 | 0.68 | 37.40 | 231.4 | 10.8 | 0.847 | 4.3 |
| 17 | 40.45 | 1.65 | 22(2) | 0.025 | 0.81 | 24.52 | 461.1 | 6.8 | 1.169 | 9.6 |
| 18 | 40.7 | 1.42 | 29(2) | 0.025 | 0.68 | 28.66 | 639.8 | 12.7 | 0.937 | 6.7 |
| 19(1) | 41 | 3.04 | 1166 | 0.038 | | 13.49 | 1170.1 | 7.7 | 1.362 | 20.7 |
| 20 | 45 | 1.12 | 182 | 0.025 | 0.62 | 40.18 | 182.6 | 5.8 | 0.753 | 4.2 |
| 21(1) | 46 | 3.2 | 3280 | 0.038 | | 14.38 | 3281.7 | 19.5 | 0.910 | 14.6 |
| 22 | 46 | 1.8 | 447 | 0.025 | 0.9 | 25.56 | 448.0 | 5.5 | 1.012 | 9.1 |
| 23 | 48.7 | 1.62 | 181 | 0.025 | 0.72 | 30.06 | 181.5 | 2.8 | 0.952 | 7.7 |
| 24 | 54 | 3.9 | 61(2) | 0.031 | 1.1 | 13.85 | 894.7 | 2.9 | 1.604 | 31.3(3) |
| 25 | 55 | 2.04 | 49(2) | 0.031 | 1.09 | 26.96 | 652.1 | 7.8 | 0.866 | 8.8 |
| 26 | 58.8 | 2.4 | 63(2) | 0.031 | 0.68 | 24.50 | 879.4 | 7.6 | 0.620 | 7.4 |
| 27 | 60 | 1.575 | 233 | 0.031 | 0.5 | 38.10 | 232.5 | 4.6 | 0.532 | 4.2 |
| 28 | 60 | 2 | 315 | 0.013 | 0.8 | 30.00 | 314.6 | 1.6 | 0.696 | 7.0 |
| 29 | 60 | 2 | 345 | 0.125 | 0.77 | 30.00 | 345.2 | 17.3 | 0.665 | 6.7 |
| 30 | 61 | 3.35 | 620 | 0.038 | 0.97 | 18.21 | 619.6 | 3.4 | 1.026 | 17.2 |
| 31(1) | 61 | 3.35 | 2040 | 0.057 | 0.71 | 18.21 | 2039.5 | 16.6 | 0.556 | 9.3 |
| 32 | 65 | 1.91 | 58(2) | 0.031 | 0.71 | 34.03 | 648.8 | 8.8 | 0.589 | 5.6 |
| 33 | 80 | 3.96 | 5096.5 | 0.020 | 0.53 | 20.20 | 5093.7 | 10.4 | 0.483 | 9.6 |
| 34 | 90 | 2.3 | 661 | 0.040 | 0.29 | 39.13 | 660.8 | 8.0 | 0.303 | 3.5 |
| 35 | 90 | 2.3 | 661 | 0.070 | 0.29 | 39.13 | 660.8 | 14.0 | 1.000 | 11.5 |

(1) there is chimney insulation, (2) total mass of the chimney in tonnes (3) vortex excitation does not need to be calculated according to Polish standard, (4) vortex excitation does not need to be calculated according to Eurocode.

Table 2

**Structural data, dynamic and damping parameters for chimneys of type 2**

| Lp, | $H$ | $H_1$ | $D_T$ | $D_B$ | $m_e$ | $\delta_s$ | $f_1$ | $\lambda$ | $m_{e\_\text{calc}}$ | $\text{Sc}_\text{calc}$ | $f_{1\text{calc}}$ | $V_{kr,1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | [m] | [m] | [m] | [m] | [kg/m] | [-] | [Hz] | [-] | [kg/m] | [-] | [Hz] | [m/s] |
| 1 | 28 | 6.16 | 1.6 | 2.304 | 255 | 0.031 |  | 17.50 | 255.1 | 4.9 | 2.774 | 22.2(3) |
| 2 | 30.5 | 7.625 | 1.4 | 2.45 | 275 | 0.025 |  | 21.79 | 274.6 | 5.6 | 2.016 | 14.1 |
| 3 | 30.5 | 7.625 | 1.4 | 2.45 | 330 | 0.025 | 1.6 | 21.79 | 331.3 | 6.8 | 2.251 | 15.8 |
| 4 | 36 | 0.72 | 1.5 | 2.325 | 230 | 0.025 | 1.04 | 24.00 | 230.2 | 4.1 | 1.180 | 8.9 |
| 5 | 36 | 12.96 | 0.4 | 0.904 | 85 | 0.019 | 0.4 | 90.00 | 84.9 | 16.1 | 0.537 | 1.1 |
| 6 | 40 | 12 | 1.45 | 2.32 | 214 | 0.038 |  | 27.59 | 214.8 | 6.2 | 1.801 | 13.1 |
| 7(1) | 43 | 12.9 | 1.8 | 3.294 | 895 | 0.031 |  | 23.89 | 894.4 | 13.7 | 0.908 | 8.2 |
| 8 | 43 | 12.9 | 1.8 | 3.294 | 300 | 0.019 | 1 | 23.89 | 299.8 | 2.8 | 1.578 | 14.2 |
| 9 | 43.5 | 15.225 | 1.68 | 3.024 | 330 | 0.025 | 0.95 | 25.89 | 331.4 | 4.7 | 1.330 | 11.2 |
| 10(1) | 44 | 11 | 1.450 | 2.596 | 490 | 0.031 |  | 30.34 | 491.5 | 11.6 | 0.705 | 5.1 |
| 11 | 44.7 | 12.069 | 2.54 | 3.581 | 500 | 0.019 | 1.2 | 17.60 | 499.6 | 2.4 | 1.626 | 20.7 |
| 12(1) | 44.7 | 12.069 | 2.54 | 3.581 | 950 | 0.031 | 0.91 | 17.60 | 950.4 | 7.3 | 1.178 | 15.0 |
| 13 | 45 | 13.5 | 1.83 | 2.928 | 270 | 0.038 |  | 24.59 | 270.7 | 4.9 | 1.512 | 13.8 |
| 14 | 45.7 | 11.882 | 1.22 | 3.05 | 190 | 0.025 | 0.92 | 37.46 | 188.4 | 5.1 | 1.193 | 7.3 |
| 15(1) | 45.7 | 10.511 | 2.2 | 3.036 | 735 | 0.031 |  | 20.77 | 734.2 | 7.5 | 0.913 | 10.0 |
| 16 | 46 | 18.4 | 1.7 | 3.74 | 262 | 0.025 | - | 27.06 | 261.1 | 3.6 | 1.535 | 13.0 |
| 17(1) | 46 | 18.4 | 1.7 | 3.74 | 650 | 0.038 | - | 27.06 | 649.5 | 13.7 | 0.966 | 8.2 |
| 18(1) | 46 | 13.34 | 1.4 | 2.8 | 450 | 0.038 |  | 32.86 | 449.8 | 14.0 | 0.702 | 4.9 |
| 19(1) | 46 | 11.04 | 2.2 | 3.432 | 745 | 0.031 |  | 20.91 | 744.8 | 7.6 | 0.928 | 10.2 |
| 20(1) | 47.5 | 15.2 | 2 | 2.66 | 755 | 0.044 | 0.9 | 23.75 | 755.0 | 13.3 | 0.753 | 7.5 |
| 21(1) | 49 | 15.19 | 2.9 | 5.22 | 955 | 0.038 |  | 16.90 | 955.6 | 6.9 | 1.080 | 15.7 |
| 22 | 55 | 17.05 | 2.14 | 3.681 | 323 | 0.025 | 1.1 | 25.70 | 322.1 | 2.8 | 1.308 | 14.0 |
| 23 | 56 | 3.92 | 2.4 | 3.768 | 780 | 0.031 | 0.83 | 23.33 | 779.6 | 6.7 | 0.817 | 9.8 |
| 24 | 60 | 36 | 1 | 1.6 | 148 | 0.031 | 0.6 | 60.00 | 148.6 | 7.4 | 0.754 | 3.8 |
| 25 | 61 | 15.25 | 2.1 | 3.675 | 410 | 0.025 | 0.66 | 29.05 | 408.8 | 3.7 | 0.861 | 9.0 |
| 26 | 68.5 | 27.4 | 3.45 | 5.693 | 680 | 0.025 | 1.12 | 19.86 | 682.9 | 2.3 | 1.234 | 21.3 |
| 27(1) | 68.5 | 27.4 | 3.45 | 5.693 | 1470 | 0.038 | 0.82 | 19.86 | 1469.6 | 7.5 | 0.836 | 14.4 |
| 28 | 72 | 23.76 | 2.5 | 4.225 | 470 | 0.025 |  | 28.80 | 469.3 | 3.0 | 0.876 | 11.0 |
| 29(1) | 72 | 23.76 | 2.5 | 4.225 | 980 | 0.038 | 0.8 | 28.80 | 979.9 | 9.5 | 0.601 | 7.5 |
| 30(1) | 74 | 18.5 | 3.5 | 5.25 | 1640 | 0.038 |  | 21.14 | 1642.2 | 8.2 | 0.589 | 10.3 |
| 31 | 74 | 24.42 | 3 | 4.5 | 595 | 0.019 | 0.66 | 24.67 | 595.6 | 2.0 | 1.060 | 15.9 |
| 32(1) | 76 | 28.88 | 4.9 | 8.33 | 2175 | 0.05 | 1.05 | 15.51 | 2174.3 | 7.2 | 1.010 | 24.7(3) |
| 33 | 76 | 23.56 | 2.75 | 6.105 | 450 | 0.025 |  | 27.64 | 453.5 | 2.4 | 0.940 | 12.9 |
| 34(1) | 76 | 19.76 | 2.9 | 4.35 | 1270 | 0.031 | 0.68 | 26.21 | 1270.1 | 7.5 | 0.553 | 8.0 |
| 35(1) | 76.2 | 15.24 | 2.62 | 3.563 | 970 | 0.038 | 0.6 | 29.08 | 971.4 | 8.6 | 0.387 | 5.1 |
| 36 | 90 | 23.4 | 4.5 | 5.49 | 1098 | 0.025 |  | 20.00 | 1098.2 | 2.2 | 0.811 | 18.2 |
| 37 | 91.5 | 29.28 | 4.88 | 8.247 | 765 | 0.031 | 1 | 18.75 | 765.1 | 1.6 | 1.118 | 27.3(3) |
| 38 | 145 | 34.8 | 6 | 10.08 | 1950 | 0.025 | 0.48 | 24.17 | 1943.5 | 2.2 | 0.456 | 13.7 |

Table 3

**Structural data, dynamic and damping parameters for chimneys of type 3**

| Lp | $H$ | $D_T$ | $D_B$ | $m_e$ | $\delta_s$ | $f_1$ | $\lambda$ | $m_{e\_\mathrm{calc}}$ | $\mathrm{Sc}_{\mathrm{calc}}$ | $f_{1\mathrm{calc}}$ | $V_{kr,1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | [m] | [m] | [m] | [kg/m] | [-] | [Hz] | [-] | [kg/m] | [-] | [Hz] | [m/s] |
| 1 | 37 | 2.45 | 3.68 | 450 | 0.038 | | 15.10 | 452.4 | 4.6 | 3.221 | 39.5(3)(4) |
| 2(1) | 49 | 0.85 | 2.32 | 245 | 0.038 | | 57.65 | 245.6 | 20.7 | 1.043 | 4.4 |
| 3(1) | 67 | 3.85 | 9.16 | 3510 | 0.038 | 0.84 | 17.40 | 3510.5 | 14.4 | 1.646 | 31.7(3) |
| 4(1) | 73 | 5.1 | 7.91 | 4100 | 0.038 | 0.64 | 14.31 | 4097.4 | 9.6 | 1.191 | 30.4(3) |
| 5 | 75 | 0.96 | 3.17 | 140 | 0.031 | 1.25 (0.8) | 78.13 | 140.0 | 7.5 | 0.875 | 4.2 |
| 6 | 77 | 3.2 | 5.54 | 1360 | 0.031 | 0.69 | 24.06 | 1361.4 | 6.6 | 1.050 | 16.8 |
| 7 | 83 | 3.2 | 6.4 | 1360 | 0.038 | 1.15 (1.2) | 25.94 | 1360.2 | 8.1 | 1.073 | 17.2 |
| 8 | 90 | 4.5 | 7.2 | 2090 | 0.031 | 0.75 (0.8) | 20.00 | 2088.6 | 5.1 | 0.978 | 22.0 |
| 9(1) | 91.5 | 4.38 | 6.92 | 2010 | 0.025 | 0.68 (0.8) | 20.89 | 2010.2 | 4.2 | 0.851 | 18.6 |

## 4. Results and discussion of chimney response

### 4.1. Along-wind response

When analyzing along-wind action, open terrain (category A according to Polish standards or its closest equivalent in Eurocode – category 2) is introduced in calculations. Two Eurocode procedures of the structural coefficient $c_sc_d$ calculations were used. In most cases, a good accordance of both methods has been obtained. The differences of the results obtained with these two procedures are less than 5% – this is consistent with Eurocode information and may confirm the accuracy of the FEM models.

In each case, higher values have been obtained with use of the second procedure. However, static FEM analyses have been performed with the use of the values of the structural coefficient from the first procedure, as more probable ones. In the presented calculations, the mode shapes of natural vibrations were obtained in FEM modal analyses and they slightly differ from those assumed in Eurocode recommendations. This could be a reason for small discrepancies in values of $c_sc_d$, as coefficients used in Eurocode are related to functions proposed by the standard.

There are comparisons of $c_sc_d$ values according to both procedures in Fig. 2.

It should be mentioned that the values of $c_sc_d$, and subsequently, wind load values are very sensitive to the choice of the terrain roughness and to the logarithmic decrement of structural damping $\delta_s$ for the analyzed chimney. Along-wind loads were calculated as static values according to respective standards and then applied to nodes of the FEM model as concentrated forces.

The normalized maximum top displacements $x/D$ in the function of chimney slenderness $\lambda$ and Scruton number Sc are presented respectively in Figs 3 and 4.

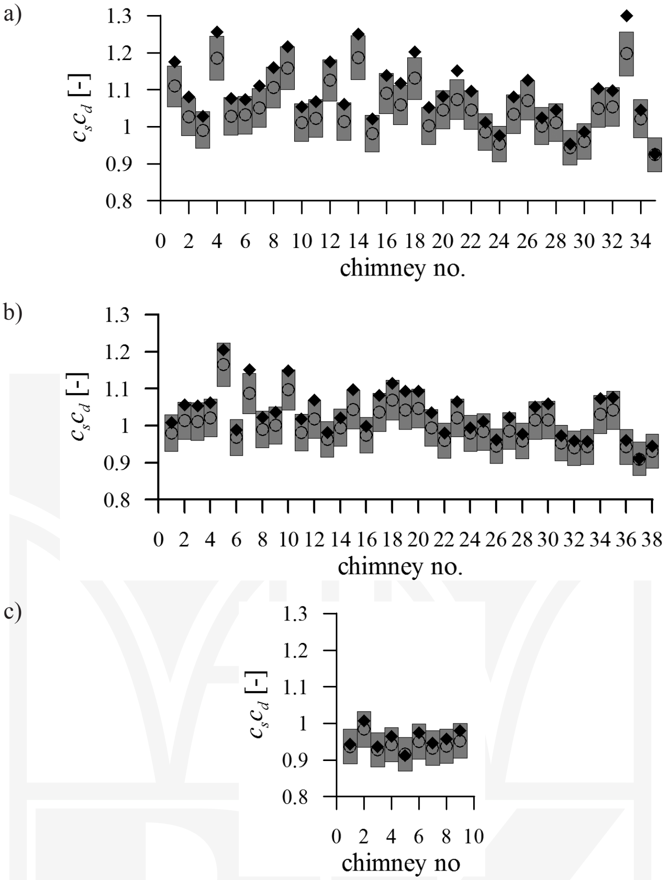

Fig. 2. Comparison of structural coefficient $c_sc_d$ for a) type 1, b) type 2, c) type 3, ○ – procedure 1, ◆ – procedure 2, grey range – procedure 1 ± 5%

Displacements calculated according to Polish standards and Eurocode are similar to each other but slightly higher for Polish standards. The first procedure of $c_sc_d$ calculations has been used. The application of the second procedure increases top displacements about 5%. Relative differences calculated as $(x_{\max,\mathrm{PN}} - x_{\max,\mathrm{Eurocode}})/x_{\max,\mathrm{PN}} \cdot 100\%$ between top displacements are in the ranges:

- 22.3%–30.8% for type 1,
- 0.6%–14.4% for type 2,
- 2%–15.4% for type 3.

The largest displacements have been obtained for chimneys of type 1. For all types values are higher for larger $\lambda$, whereas no distinct dependence on Sc have been noticed. The highest values of top displacements in Fig. 4a,b,c are related to chimneys with relatively small diameter and high slenderness. The probable reason for differences between codes is that Polish standards distinguish 3 terrain categories whereas Eurocode – five. The transition between categories is always questionable.

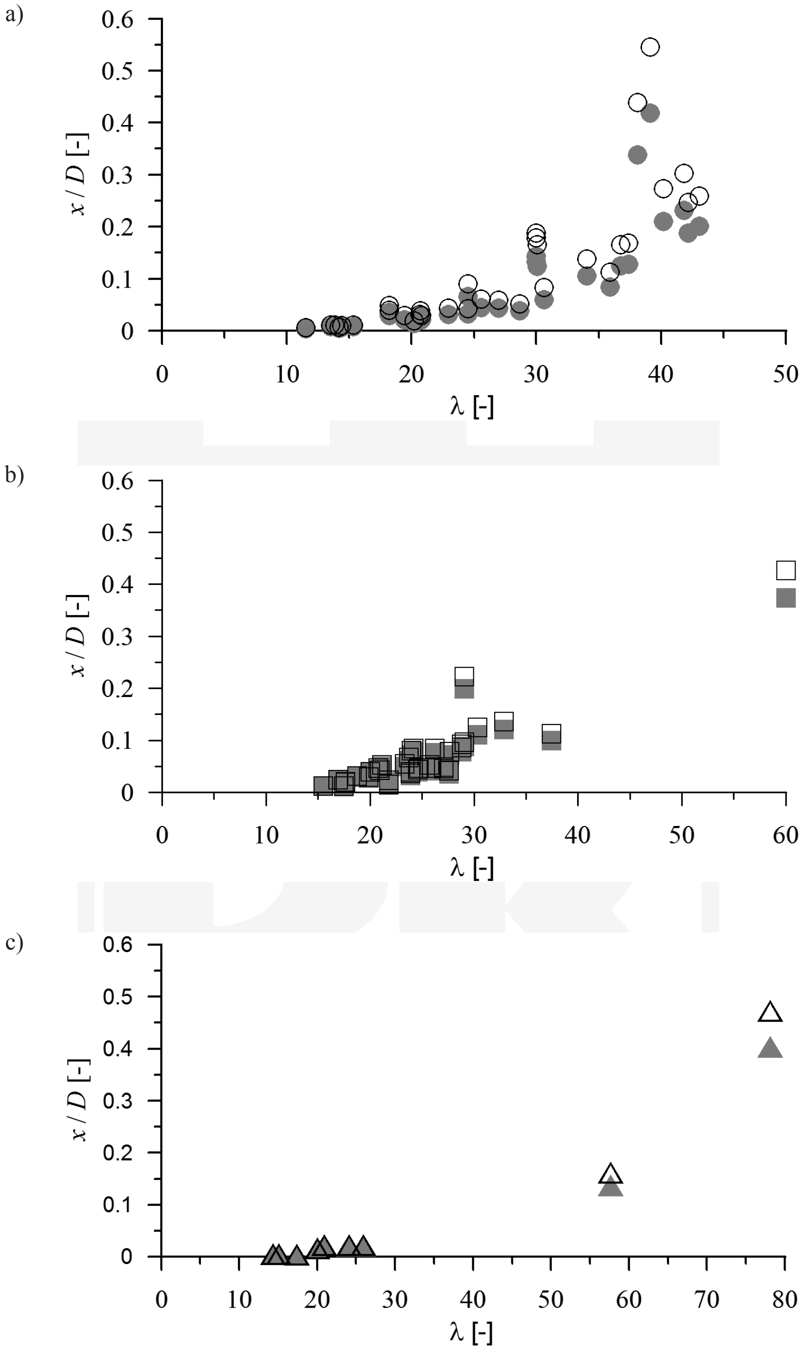

Fig. 3. Normalized top displacements in along-wind direction in dependence on slenderness λ for a) type 1, ○ – Polish standards, ● – Eurocode, b) type 2, □ – Polish standards, ■ – Eurocode, c) type 3, △ – Polish standards, ▲ – Eurocode

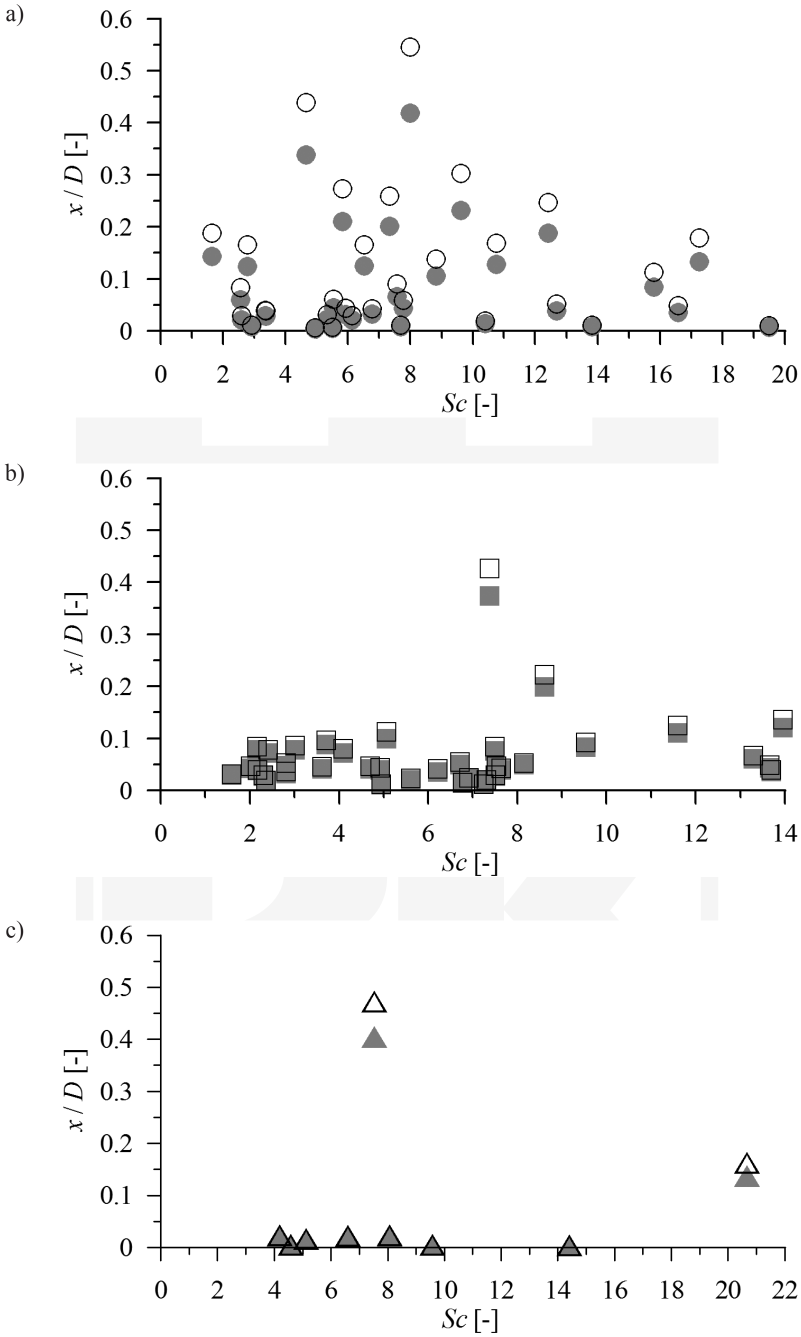

Fig. 4. Normalized top displacements in along-wind direction in dependence on Scruton number Sc for a) type 1, ○ – Polish standards, ● – Eurocode, b) type 2, □ – Polish standards, ■ – Eurocode, c) type 3, △ – Polish standards, ▲ – Eurocode

### 4.2. Crosswind response

Crosswind load caused by vortex excitation has been analyzed according to three approaches: one recommended by Polish standards and two recommended by Eurocode. All parameters describing respective loads have been assumed according to code's rules. There are dependencies between maximum normalized top displacements and $\lambda$, Sc and $f_1$ shown in Figs 5–7. The use of normalized displacements $y/D$ on vertical axis shows in some cases characteristics trends which are not visible when only $y$ is used. In case of Eurocode procedures No. 1 and No. 2 top displacements caused by vortex shedding have been calculated in the first step (eqs 6, 7) and then static inertia forces (eq. 5) have been applied to nodes of the FEM models. Final displacements obtained in static analyses are very similar to the ones caused by vortices only.

Displacements calculated with Polish standards are in accordance with those calculated with procedure 1 from Eurocode and are slightly higher. A similar model is adopted in both methods but the Polish standard assumes constant correlation length independent from lock-in effect and, in the majority of cases, it is longer than that determined from the iterative procedure in Eurocode. (Fig. 8). Another reason for small discrepancies is the Strouhal number value which is equal to 0.2 (Polish standard) and 0.18 (Eurocode). This leads to different critical wind speeds. The recommended structural logarithmic decrement of damping also differs between both codes. In the paper, the same level of damping based on measurements has been assumed; therefore, it does not influence the results.

On the other hand, displacements obtained according to procedure 2 from Eurocode are significantly higher. Top displacements according to procedure 2 are higher than those obtained with procedure 1, on average:

- type 1 – 4.17 times (in two cases displacements are lower, in two cases displacements are much higher, these results have not been averaged);
- type 2 – 4.8 times (in two cases displacements are lower, these results have not been averaged);
- type 3 – 5.3 times (in one case displacements are lower, in one case much higher, these results have not been averaged). Moreover, the representative number of chimneys of type 3 is quite low.

Considering procedure 2, it must be underlined that lower displacements have been obtained for high Scruton number values which means that damping forces are high when compared to inertia forces. When the Scruton number is high, the standard deviation of displacements $\sigma_y$ (eq. 8) and $y_{\max}$ (eq. 7) is very small.

There is a clear dependence between the maximum normalized top displacements and Scruton number. Obviously, values of $y/D$ decrease with an increase of Sc – almost linearly in the case of procedure 2 and according to exponential function in the case of Polish standard and procedure 1. Such a tendency is clearly visible mainly for chimneys of type 2.

There is no clear dependence between $y/D$ and slenderness $\lambda$ and values obtained from procedure 2 are higher for all ranges of $\lambda$.

There is either no clear dependence between $y/D$ and $f_1$. The range of first frequencies for the analyzed chimneys is 0.303–3.221 Hz. A higher $f_1$ means a higher critical wind speed but on the other hand, it also means a higher stiffness of the structure.

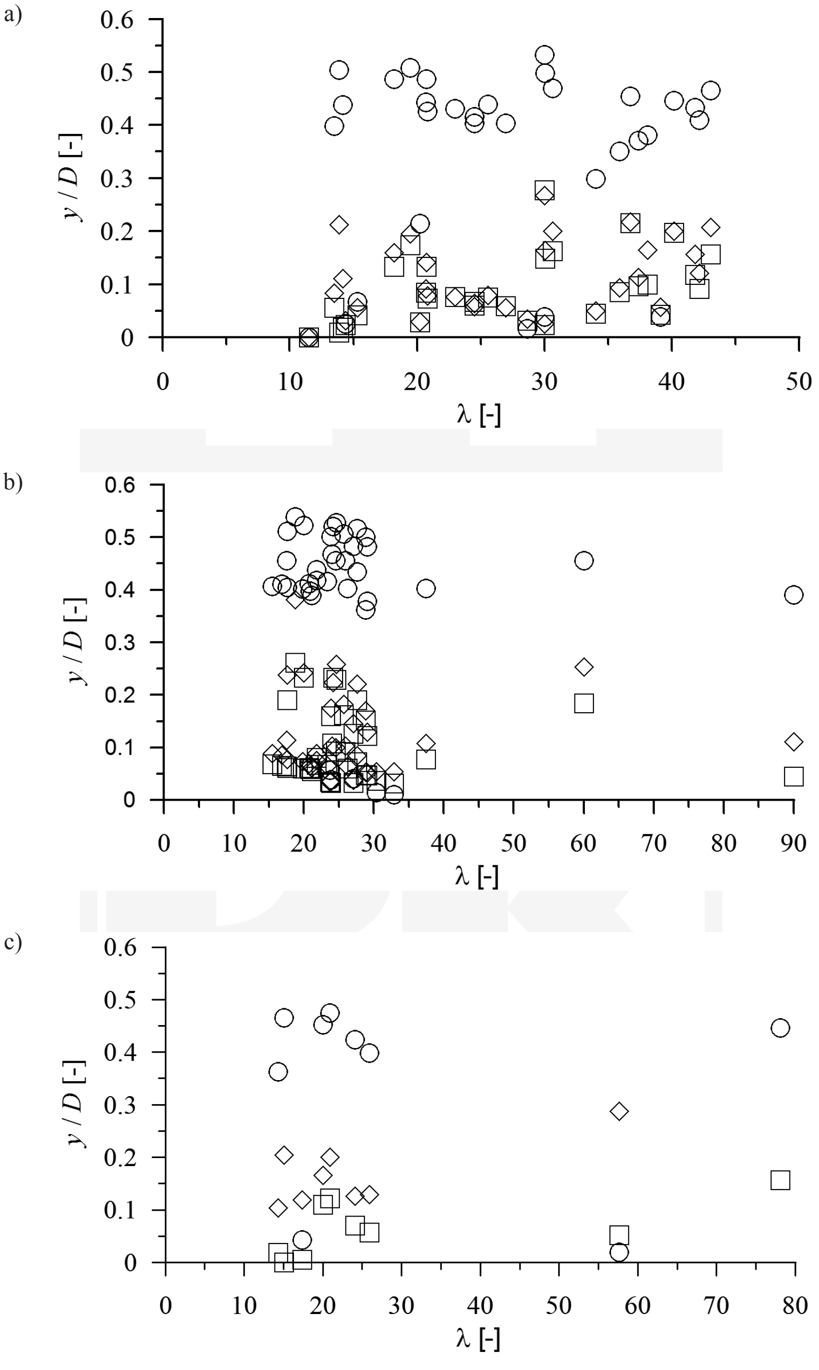

Fig. 5. Normalized top displacements in crosswind direction in dependence on slenderness λ, a) type 1, b) type 2, c) type 3, ◇ – Polish standard, □ – Eurocode, procedure 1, ○ – Eurocode, procedure 2

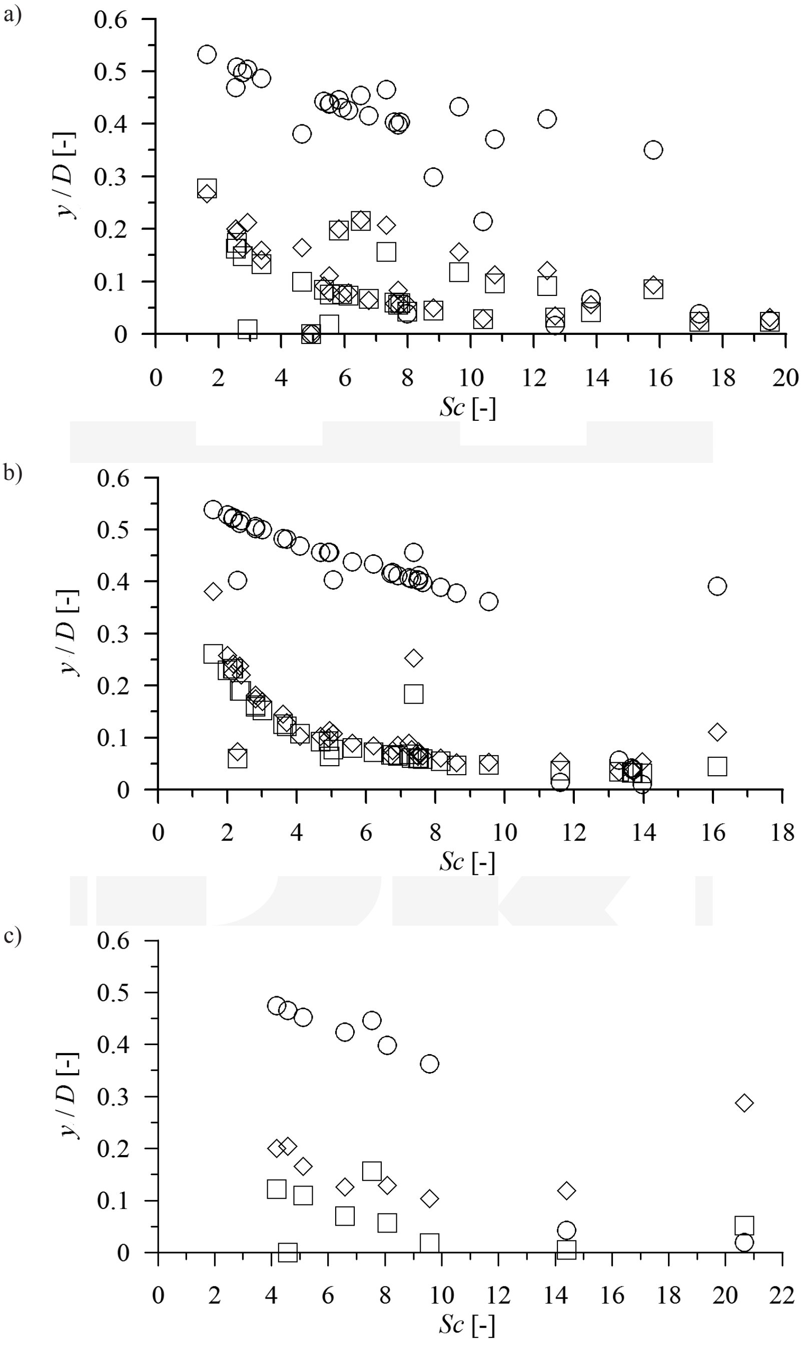

Fig. 6. Normalized top displacements in crosswind direction in dependence on Scruton number Sc, a) type 1, b) type 2, c) type 3, ◇ – Polish standard, □ – Eurocode, procedure 1, ○ – Eurocode, procedure 2

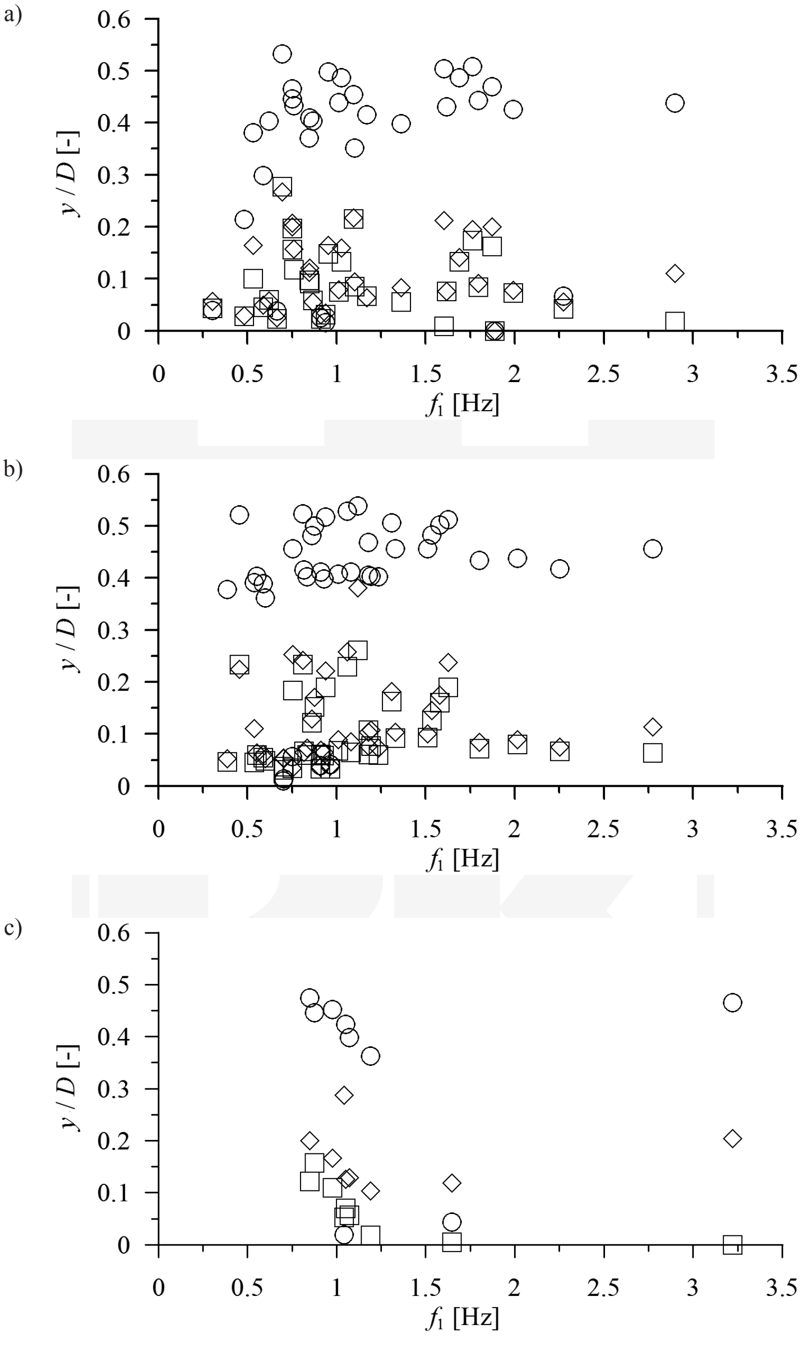

Fig. 7. Normalized top displacements in crosswind direction in dependence on the first natural frequency $f_1$, a) type 1, b) type 2, c) type 3, ◇ – Polish standard, □ – Eurocode, procedure 1, ○ – Eurocode, procedure 2

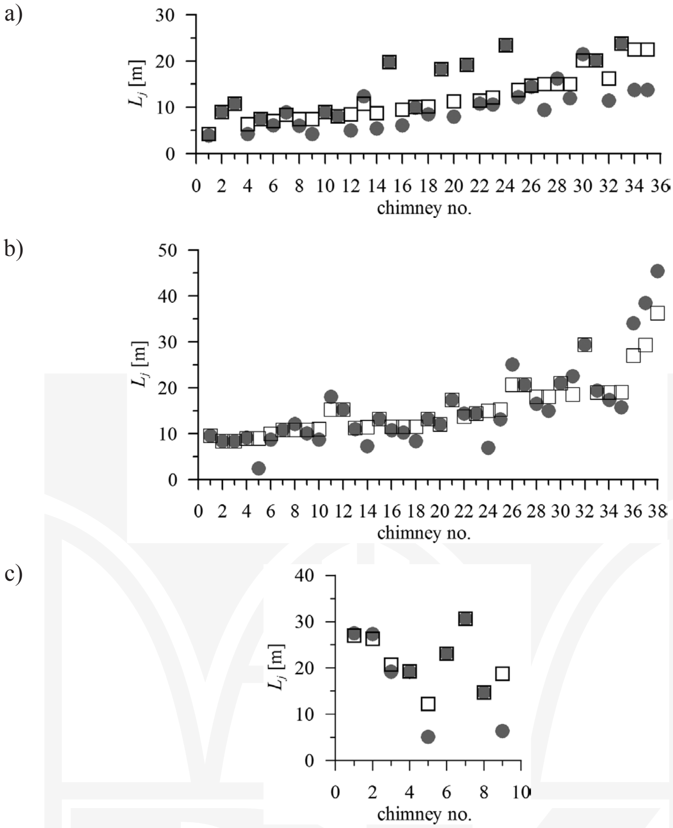

Fig. 8. Correlation length: a) type 1, b) type 2, c) type 3, ☐ – polish standard, ● – Eurocode

### 4.3. Comparison of displacements in along-wind and crosswind responses

There are comparisons of normalized top displacements obtained in along-wind and crosswind load analyses presented in Fig. 9. As can be seen, in almost all cases the crosswind load causes larger displacements.

## 5. Conclusions

Deflections at the top of the chimneys in the case of along-wind action calculated with each of the standards are similar. One of the main factors influencing discrepancies is the definition of terrain roughness in different standards. Additional discrepancies are produced with different assumed values of structural damping or the procedure of the structural coefficient calculation that has been used.

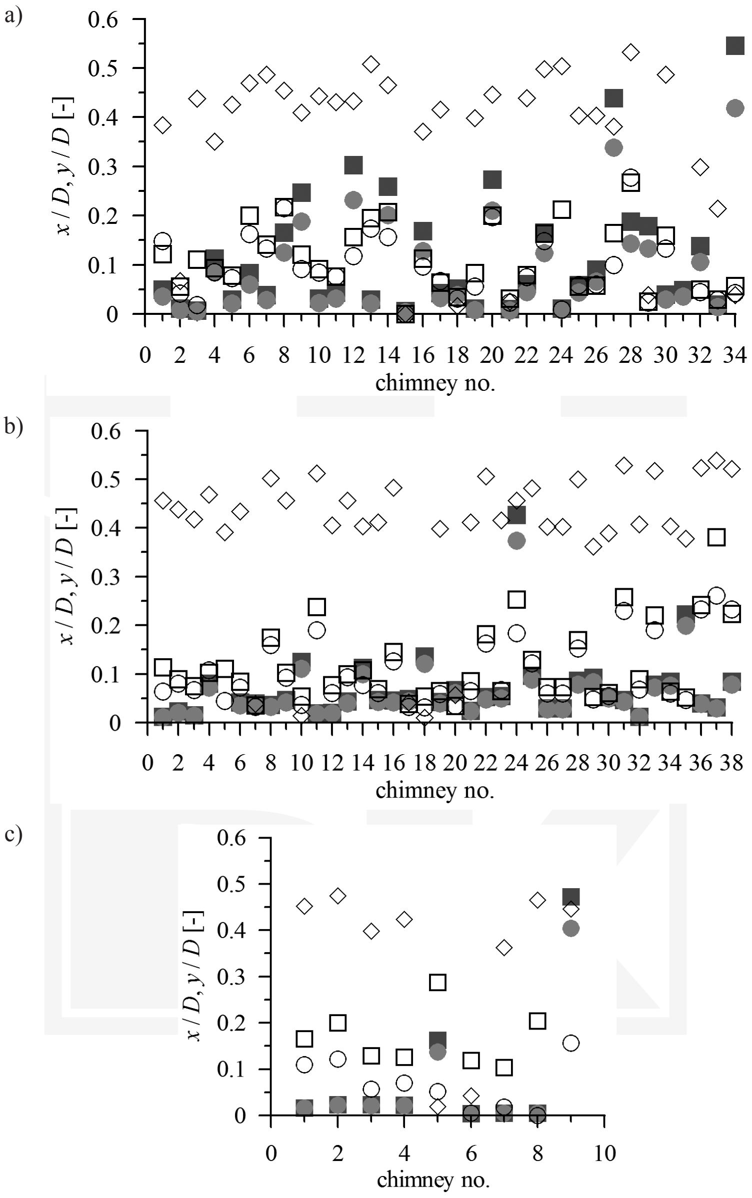

Fig. 9. Normalized top displacements in along-wind and crosswind directions for a) type 1, b) type 2, c) type 3, ■ – along-wind, Polish standard, ● – along-wind, Eurocode, □ – crosswind, Polish standard, ○ – crosswind, Eurocode, procedure 1, ◇ – crosswind, Eurocode, procedure 2

Significant differences are noticeable when crosswind action is considered. In the case of lower Sc numbers, the obtained values of deflections are higher for each type of chimney and such conclusion is in force for all natural frequencies. There is no significant relation of deflections to the slenderness of the structure $\lambda$ as well as to natural frequency $f_1$. The main factors influencing the results are: assumed value of St number; structural damping; assumed area of vortex excitation; and most of all, the choice of analytical procedure. Results obtained due to the Polish standard and Eurocode 1, procedure 1 are quite similar, whereas procedure 2 gives top displacements that are a few times higher.

Generally, the calculated deflections generated by the along-wind action are a few times smaller than the ones generated by the crosswind action.

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