Computational determination of aerodynamic resistance for high truss structures like telecommunications towers is the subject of this study. Normalized procedures were presented with an example of an existing structure concerning the total wind coefficient. The results of calculations along with their broad elaboration and interpretation have been presented. Analyses and calculations were conducted for a tower of height equal to 84 metres and of a triangular cross section. The structure is characterized by round full rods as the legs of the tower and hot-rolled angle bars as the bracing. Two computational approaches were applied providing the results for each of them. The achieved results allow for stating that selection of a computational standard procedure should be adequate to an analysed structure and its characteristic features. The information included in the article is particularly useful in case of the determination of carrying capacity of existing tower structures on the basis of Eurocode standards.

Keywords: aerodynamic resistance, total wind force coefficient, telecommunication towers, linear ancillary item

1. Introduction

Introduction of European standards in recent times in the Polish regulations caused great changes in the determination of carrying capacity of individual civil structures. The analysis of carrying capacity with respect to current provisions is still a challenging problem for designers and building surveyors. This results from the fact that not only did the concepts of determination of the carrying capacity of individual structural elements change but the way the load is formulated changed as well. There are particular situations where objects designed a dozen years ago, based on completely different requirements and standard procedures must be recalculated. Steel structures of telecommunication towers are a typical example of such a situation.

The rapidly growing market for telecommunication services along with new hardware requirements and social needs are the signs of our time. Therefore, mobile telecommunication operators are constantly modifying their infrastructure and electronic devices due to this demanding situation. Considering telecommunication equipment and hardware, we can take devices like radio modules, panel antennas, microwave dishes, etc. All such installations are mounted on support structures like telecommunications towers. Every modification of such equipment affects main structure characteristic parameters such as magnitude of loading, aerodynamic factors and etc. It provides a necessity for recalculation of the tower carrying capacity.

The study is devoted to the computational determination of aerodynamic resistance of tower telecommunication structures based on the formulae included in the standards [1].

2. Problem description

In general sense the coefficient of aerodynamic resistance (or the total wind force coefficient or wind drag) depends on [2]: shape of a cross section of bars of a lattice structure, their slenderness, shape of a horizontal section of a tower and a direction of wind relative to walls of an object. The definition of wind drag given in [1] is as follows – resistance to the flow of wind offered by elements of a tower or a guyed mast and any ancillary items that it supports, given by the product of a drag coefficient and a reference projected area, including ice where relevant.
As it is described in [3], the term “wind loading resistance” is generally adopted to encompass the combination of area, shielding effects and drag coefficients. The simplest analytical explanation of wind mean loading on a tower may be expressed as:

$$P = \frac{1}{2} \rho V^2 c_f A$$

(1)

where: $\rho$ is the air density [kg/m$^3$], $V$ [m/s] is the relevant wind velocity, $c_f$ is the drag coefficient related to the area $A$ [m$^2$].

Considering wind resistance, which should be expressed as the $R = c_f A$, we have to realize that the most difficult aspect to codify is the treatment of ancillaries mounted on the structure. Additional elements can take different forms, in terms of position and of shapes, covering ladders, feeders, safety access rails, antennas and dishes, etc. [3].

In case of telecommunication towers with higher complexity (e.g. flat-sided and circular-section members), calculation problem of aerodynamic resistance seems more challenging. For towers made from profiles of different kind, loaded with cable and climbing ladders or other linear ancillaries like antennas and their support structures, correct estimation of the aerodynamic resistance is a demanding task. We should include interactions of structural elements and accessories, their mutual shielding effect as well as different flow patterns of elements of flat sided or circular edges.

The determination of the aerodynamic coefficient according to standard [4], which is widely described in publication [5], was a relatively simple procedure. The solidity ratio of one (usually front) face of the spatial truss is the main parameter in this approach. It should be described as follows:

$$\varphi_L = \frac{F + F_L \cdot 0.6}{S}$$

(2)

where: $F$ is the shadow area (area of the solid members in the appropriate face) of every structural element of the front face, on a plane normal to wind direction, $F_L$ is the shadow area of the linear ancillaries of the tower, $S$ is the area of the considered contour (elevation).

For a tower with circular-section legs and flat-sided braces, the coefficient of aerodynamic resistance is described by the formula given in [4] as:

$$c_f = 3.5 - 4.0 \cdot \varphi, \quad 0 < \varphi < 0.37$$

(3)

Similar considerations can be carried out according to standard [1]. However, we should emphasize that the degree of their complexity is definitely greater.

Considering wind loading of steel skeletal telecommunication towers, we should realize that this particular kind of loading is the crucial one, and it decides about the cross-sections of structural members, the geometrical dimensions of a tower, the total weight of a structure, etc. Taking this fact into consideration, it is worth presenting the formulae given in [1] that are describing the wind force in the direction of the wind on the tower.

The mean wind load in the direction of the wind on the tower is described as follows:

$$F_{m,W}(z) = \frac{q_p}{1 + 7J_v(z)} \sum c_f A_{\text{ref}}$$

(4)

where: $J_v$ is the turbulence intensity, $q_p$ [kN/m$^2$] is the peak velocity pressure, $A_{\text{ref}}$ [m$^2$] is the reference area of the structure (projected area), $z$ [m] is the height above ground level and $c_f$ is the total wind force coefficient.

On the other hand, we have to take the equivalent gust wind load in the direction of the wind into consideration during the carrying capacity analysis which is determined as follows:

$$F_{r,W}(z) = F_{m,W}(z) \left[1 + \left(1 + 0.2 \left(\frac{z_m}{h}\right)^2\right) \left[1 + 7J_v(z)\right] c_s c_d - 1\right]$$

(5)

where: $c_s$ is the structural factor, $z_m$ [m] is the height above the base at which a load effect is required, $c_s(z_m)$ is the orography factor and $h$ [m] is the overall tower height.

As we can find in Equation (4), the magnitude of the mean wind load depends on four parameters where the most difficult to determine via analytical calculations, as it was mentioned above, is the total wind force coefficient.

3. Analyzed structure

Analysis has been performed on the basis of the existing telecommunication tower illustrated in Fig. 1 of height equal to 84 meters. The construction is divided into 14 sections with their height equal to 6.0 meters. The lowest section S-14 is presented in Fig. 1 in axonometric view. The static scheme of such a structure is a spatial truss fixed in ground by the foundations.
ANALYTICAL DETERMINATION OF AERODYNAMIC RESISTANCE OF THE SKELETAL TELECOMMUNICATION TOWERS

The leg members of the tower (the main load-bearing components) consist of circular full rods and primary bracing members with hot-rolled angle bars. Feeders, cables and climbing ladder (linear ancillary) is placed centrally inside the tower. The ladder is made of two vertically situated cold-formed C-bars connected by circular rods at one end, and with brackets for feeders and cables at the other end as it is presented in Figure 1 and Figure 2.

In Figure 2 there is presented the cross section of the tower above the service platform. We can also find the cable-climbing ladder placed in the center of the structure. Numbers 1, 2 and 3 on the drawing denote particular faces of the tower. An arrow presents the wind direction where $\Theta_1$ is the angle of incidence of the wind normal to face 1. As we can observe in the attached picture taken on the existing tower, there are cables and feeders on the rear side of the ladder and also on the cantilevers mounted to the front-climbing part.

Table 1 presents individual elements for every section of the structure such as leg members, primary and secondary bracing. The most important part of the data collected in Table 2 are: $A_{ij}$, that is the total projected area when viewed normal to the face of the flat-sided section members in the face (1, 2 or 3) where $A_{ij}$ is the total projected area normal to
the face of the circular-section members in the face (1, 2 or 3) in sub critical regimes. Especially important for further considerations is the division the projected area of an individual section for circular and flat-sided members. It results from the necessity of consideration of different flow patterns around sharp edges and circular members. For circular members the flow is critically dependent on wind velocity, or in aerodynamic terms, on the Reynolds number.

The collected areas of the analyzed structure are specified for the angle of incidence of the wind $\Theta_1$ equal to 0.

The total area projected normal to a face (e.g. 1) of the structural components without ancillaries should be expressed as:

$$A_{x,1} = A_{c,1} + A_{f,1}$$  \hspace{1cm} (6)

Table 2 presents the elements and their projected areas of the cable-climbing ladder. As it can be found, there is a division of the flat-sided elements $A_{f}$ and the circular members $A_{c}$, and we notice that for this particular structure, the projected area of the ladder is equal for all the tower sections.

It should be emphasized that the total area of the cable-climbing ladder is equal to:

$$A_t = A_{c} + A_{f}$$  \hspace{1cm} (7)

4. Aerodynamic resistance calculations

All calculations of the total wind force coefficient are based on one of the most important parameters in the theory of aerodynamic resistance of skeletal structures, the solidity ratio. Standard [5] describes it as follows:

$$\varphi = \frac{A}{A_c}$$  \hspace{1cm} (8)

where: $A$ [m$^2$] is the sum of projected areas of the members and $A_c$ [m$^2$] is the overall envelope area.

Table 1. Sections of the towers with their projected areas for $\Theta_1 = 0^\circ$

<table>
<thead>
<tr>
<th>Section</th>
<th>Legs</th>
<th>Primary bracing</th>
<th>Secondary bracing</th>
<th>$A_{x,1}$ [m$^2$]</th>
<th>$A_{c,1}$ [m$^2$]</th>
<th>$A_{c,2}$ [m$^2$]</th>
<th>$A_{c,3}$ [m$^2$]</th>
<th>$A_{c,4}$ [m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-1</td>
<td>Ø80</td>
<td>L 90x60x8</td>
<td>C 65</td>
<td>0.96</td>
<td>1.10</td>
<td>0.96</td>
<td>0.86</td>
<td>0.96</td>
</tr>
<tr>
<td>S-2</td>
<td>Ø80</td>
<td>L 90x60x8</td>
<td>C 65</td>
<td>1.48</td>
<td>0.47</td>
<td>1.48</td>
<td>0.27</td>
<td>1.48</td>
</tr>
<tr>
<td>S-3</td>
<td>Ø90</td>
<td>L 90x60x8</td>
<td>C 65</td>
<td>1.69</td>
<td>0.48</td>
<td>1.69</td>
<td>0.22</td>
<td>1.69</td>
</tr>
<tr>
<td>S-4</td>
<td>Ø90</td>
<td>L 90x60x8</td>
<td>C 65</td>
<td>1.61</td>
<td>0.93</td>
<td>1.61</td>
<td>0.60</td>
<td>1.61</td>
</tr>
<tr>
<td>S-5</td>
<td>Ø100</td>
<td>L 90x60x8</td>
<td>C 65</td>
<td>1.20</td>
<td>1.62</td>
<td>1.20</td>
<td>1.06</td>
<td>1.20</td>
</tr>
<tr>
<td>S-6</td>
<td>Ø100</td>
<td>L 120x80x10</td>
<td>C 65</td>
<td>1.20</td>
<td>1.92</td>
<td>1.20</td>
<td>1.27</td>
<td>1.20</td>
</tr>
<tr>
<td>S-7</td>
<td>Ø100</td>
<td>L 120x80x10</td>
<td>C 65</td>
<td>1.20</td>
<td>2.47</td>
<td>1.20</td>
<td>1.52</td>
<td>1.20</td>
</tr>
<tr>
<td>S-8</td>
<td>Ø110</td>
<td>L 120x80x10</td>
<td>L 100x100x10</td>
<td>1.32</td>
<td>2.04</td>
<td>1.32</td>
<td>1.41</td>
<td>1.32</td>
</tr>
<tr>
<td>S-9</td>
<td>Ø110</td>
<td>L 150x100x10</td>
<td>L 100x100x10</td>
<td>1.32</td>
<td>2.54</td>
<td>1.32</td>
<td>1.74</td>
<td>1.32</td>
</tr>
<tr>
<td>S-10</td>
<td>Ø110</td>
<td>L 150x100x10</td>
<td>L 120x120x10</td>
<td>1.32</td>
<td>2.85</td>
<td>1.32</td>
<td>1.88</td>
<td>1.32</td>
</tr>
<tr>
<td>S-11</td>
<td>Ø120</td>
<td>L 150x100x10</td>
<td>L 120x120x10</td>
<td>1.44</td>
<td>3.01</td>
<td>1.44</td>
<td>1.94</td>
<td>1.44</td>
</tr>
<tr>
<td>S-12</td>
<td>Ø120</td>
<td>L 150x100x10</td>
<td>L 150x150x12</td>
<td>1.44</td>
<td>3.61</td>
<td>1.44</td>
<td>2.23</td>
<td>1.44</td>
</tr>
<tr>
<td>S-13</td>
<td>Ø120</td>
<td>L 200x100x10</td>
<td>L 150x150x12</td>
<td>1.44</td>
<td>3.83</td>
<td>1.44</td>
<td>2.30</td>
<td>1.44</td>
</tr>
<tr>
<td>S-14</td>
<td>Ø120</td>
<td>L 200x100x10</td>
<td>L 200x200x20</td>
<td>1.44</td>
<td>4.03</td>
<td>1.44</td>
<td>2.42</td>
<td>1.44</td>
</tr>
</tbody>
</table>

Table 2. The elements of the cable-climbing ladder

<table>
<thead>
<tr>
<th>Flat-sided members</th>
<th>Circular section members</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access rail [m$^2$]</td>
<td>Feeders and cables [m$^2$]</td>
</tr>
<tr>
<td>Guide rails [m$^2$]</td>
<td>Steps [m$^2$]</td>
</tr>
<tr>
<td>Cable cantilevers [m$^2$]</td>
<td>$A_f$ [m$^2$]</td>
</tr>
<tr>
<td>$A_{c}$ [m$^2$]</td>
<td>$A_{c}$ [m$^2$]</td>
</tr>
</tbody>
</table>

Table 3. Envelope areas $A_{c}$ [m$^2$] for particular sections of the tower

<table>
<thead>
<tr>
<th>Section</th>
<th>$A_{c}$ [m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-1</td>
<td>15.0</td>
</tr>
<tr>
<td>S-2</td>
<td>16.8</td>
</tr>
<tr>
<td>S-3</td>
<td>20.4</td>
</tr>
<tr>
<td>S-4</td>
<td>24.0</td>
</tr>
<tr>
<td>S-5</td>
<td>27.6</td>
</tr>
<tr>
<td>S-6</td>
<td>31.2</td>
</tr>
<tr>
<td>S-7</td>
<td>34.8</td>
</tr>
<tr>
<td>S-8</td>
<td>38.4</td>
</tr>
<tr>
<td>S-9</td>
<td>42.0</td>
</tr>
<tr>
<td>S-10</td>
<td>45.6</td>
</tr>
<tr>
<td>S-11</td>
<td>49.2</td>
</tr>
<tr>
<td>S-12</td>
<td>52.8</td>
</tr>
<tr>
<td>S-13</td>
<td>56.4</td>
</tr>
<tr>
<td>S-14</td>
<td>60.0</td>
</tr>
</tbody>
</table>
The envelope areas for the sections of the analyzed structures are collected in Table 3.

It should be underlined that Equation (8) expresses the structure shadow area only, and the formula does not include ancillaries like a ladder, etc. It should be noticed that the data collected in Table 1 indicates that for the individual faces of the tower (1, 2 or 3) we obtain different solidity ratios ($\varphi_1$, $\varphi_2$ or $\varphi_3$ respectively).

According to standard [1] and the recommendations given in [3, 6], calculations of the tower aerodynamic resistance might be considered applying two independent approaches. It depends on the systems of the tower structures and that may be generally divided into symmetrical structures with limited ancillaries and structures containing ancillaries.

To present the algorithm of the calculations, detailed expression, formulae, the results are going to be shown on one chosen section of the tower – S-10. The results for other sections take a tabular form. All the calculations are provided for the angle of incidence of the wind $\Theta_1 = 0^\circ$.

### 4.1. Total wind force coefficient – general method

According to [1], the total wind force coefficient in direction of wind over a section of the structure should be taken as:

$$ c_{f,10} = c_{f,S,10} + c_{f,A,10} $$

where: $c_{f,S,10}$ is the wind force coefficient of bare structure section S-10 determined using a solidity ratio $\varphi$, $c_{f,A,10}$ is the wind force coefficient of the ancillaries in section S-10.

It is worth emphasizing that in this approach only face 1 with the feeder-cable ladder should be considered.

The solidity ratio for section S-10 is equal to:

$$ \varphi_{10} = \frac{A_{c,10} + A_{e,10} + A_{a,c} + A_{a,f}}{A_c} = 0.153 $$

The force coefficients for sections composed of flat sided, sub critical circular members are given by:

$$ c_{f,0,f,10} = C_1 \left(1 - C_2 \cdot \varphi_{10}\right) = 2.71 $$

$$ c_{f,0,e,10} = C_1 \left(1 - C_2 \cdot \varphi_{10}\right) + (C_1 + 0.875) \varphi_{10} = 1.55 $$

where: $C_1$ is equal to 1.9 and $C_2$ is 1.4 for the triangular structures.

The value of the overall normal force coefficient $c_{f,S,0,10}$ that is applicable to the structural framework of triangular section S-10 composed of both flat-sided and circular sections should be calculated as:

$$ c_{f,S,0,10} = c_{f,0,f,10} \left(\frac{A_{f,1,10} + A_{a,f}}{A_{s,1,10} + A_s}\right) + c_{f,0,e,10} \left(\frac{A_{e,1,10} + A_{a,e}}{A_{s,1,10} + A_s}\right) = 2.21 $$

The wind incidence factor $K_{\Theta} = 1.0$ for $\Theta_1 = 0^\circ$, thus the wind force coefficient of structure section S-10 is equal to:

$$ c_{f,S,10} = K_{\Theta} c_{f,S,0,10} = 2.21 $$

Let us focus now on the part of Equation (9) that describes participation of the feeder-climbing ladder in overall coefficient wind force. Reduction factor that takes into account the shielding of the component by the structure itself for the triangular cross section of the tower and ancillaries placed internally to the structure $K_A$ is equal to 0.8. Overall normal drag coefficient appropriate for the item and its Reynolds number for flat-sided sections given in [1] is

$$ c_{f,A,0} = 2.0 $$

It’s necessary to underline that in this codified approach the ladder with all its elements such as cables, feeders, steps, access rails, etc. is treated as a one solid component. Taking it into our consideration, an analyzed ancillary should be treated as a one, flat-sided element as given above. In the analysis of the aerodynamic resistance of the ladder, $\psi$ denotes an angle of wind incidence to the longitudinal axis of a linear member. For the purpose of these calculations, the angle $\psi$ takes the most adverse value $90^\circ$.

The conclusions given above lead us to the determination of the wind force coefficient of the ancillaries in section S-10:

$$ c_{f,A,10} = K_A \cdot c_{f,A,0} \cdot \sin^2 \psi = 1.6 $$

During the calculation process, we obtained all the parameters that allow us to determine the total wind force coefficient in the direction of the wind over section S-10:

$$ c_{f,10} = c_{f,S,10} + c_{f,A,10} = 3.81 $$

The results for other sections are collected in Table 4 that contains all the parameters described in the previous considerations.
4.2. Total wind force coefficient – method for special cases

The total wind force coefficient in this analytical approach may be determined according to [1] from expression as follows

\[ \cos \Theta \left( \frac{3 \Theta_s}{4} \right) + \sin \Theta \left( \frac{3 \Theta_s}{4} \right) \]  

(17)

The main difference between the presented methods (the general and one for special cases) is the treatment of the sections as general. In 4.1., there is an assessment that for obtaining aerodynamic resistance we need to take into consideration only face 1 and the feeder-climbing ladder behind. Here faces 1, 2 and 3 are included in calculations as well as the fact that there are some shielding effects expressed in the analysis by a shielding factor. According to standard [1], for section S-10 it should be calculated as follows:

\[ \eta_{F,10} = \left( 1 - \frac{A_{S,1,10} + A_{A,1,10}}{45.60} \right) \]  

(18)

\[ \eta_{e,10} = \eta_{F,10} \left( A_{F,1,10} + 0.83 \cdot A_{e,1,10} + A_{e} \right) \left( A_{S} + A_{A} \right) \]  

(19)

To obtain the total force coefficient we should calculate factors for every face, treated here as a single frame. The results and formulae are collected in Table 5.

It should be explained that: \( c_{f,S1,10} \) is the force coefficient appropriate for face 1 in section S-10, \( c_{f,A1,10} \) is the wind force coefficient appropriate for face 1 in section S-10 for the ancillary items are not treated as structural members. For circular members \( c_{f,A1,10} \) they are equal to 0.5 and for flat-sided 2.0 respectively. In Equation (17) there are \( c_{1,e}, c_{2,e} \) factors that denote effective wind force coefficients given for triangular structures by following:

\[ \left( c_{1,e} + \frac{0.67 \cdot \eta_{e}}{2} \right) K_{\Theta} = 2.13 \]  

(20)

\[ \left( c_{2,e} + \frac{0.67 \cdot \eta_{e}}{2} \right) K_{\Theta} = 2.24 \]  

Finally, the total wind force coefficient given by Equation (17) takes the value of

\[ c_{f,10} = c_{e,10} = 2.13 \]  

(20)

In Table 6 the results of \( c_f \) for other sections of the analyzed tower are collected.

5. Comparison of the results

Comparison of the results obtained through two independent standard methods is presented in the graphical form in Figure 3.
Table 5. The calculation parameters

<table>
<thead>
<tr>
<th>Face</th>
<th>Coefficient</th>
<th>Formula</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$c_{f,f,1.10}$</td>
<td>$1.58 + 1.05(0.6 - \varphi_{1.10})^{1.8}$</td>
<td>1.83</td>
</tr>
<tr>
<td></td>
<td>$c_{f,e,3.10}$</td>
<td>$\left(0.6 + 0.4\varphi_{2.10}^2\right)c_{f,f,1.10}$</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td>$c_{f,S1.10}$</td>
<td>$c_{f,f,1.10}\frac{A_{f,1.10}}{A_s} + c_{f,e,1.10}\frac{A_{e,1.10}}{A_s}$</td>
<td>1.60</td>
</tr>
<tr>
<td></td>
<td>$c_{1.10}$</td>
<td>$c_{f,S1.10}\frac{A_{S,1.10}}{A_s + A_d} + c_{f,e,1.10}\frac{A_{e,1.10}}{A_s + A_d}$</td>
<td>1.40</td>
</tr>
<tr>
<td></td>
<td>$f\frac{A_{A,f}}{A_s + A_d} + c_{f,e,1.10}\frac{A_{A,e}}{A_s + A_d}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2(3)</td>
<td>$c_{f,f,2.10}$</td>
<td>$1.58 + 1.05(0.6 - \varphi_{2.10})^{1.8}$</td>
<td>1.84</td>
</tr>
<tr>
<td></td>
<td>$c_{f,e,2.10}$</td>
<td>$\left(0.6 + 0.4\varphi_{2.10}^2\right)c_{f,f,2.10}$</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>$c_{f,S2.10}$</td>
<td>$c_{f,f,2.10}\frac{A_{f,2.10}}{A_s} + c_{f,e,2.10}\frac{A_{e,2.10}}{A_s}$</td>
<td>1.54</td>
</tr>
<tr>
<td></td>
<td>$c_{2.10}$</td>
<td>$c_{f,S2.10}\frac{A_{S,2.10}}{A_s + A_d}$</td>
<td>1.54</td>
</tr>
</tbody>
</table>

Table 6. Total wind force coefficients obtained via method for special cases

<table>
<thead>
<tr>
<th>Section</th>
<th>S-1</th>
<th>S-2</th>
<th>S-3</th>
<th>S-4</th>
<th>S-5</th>
<th>S-6</th>
<th>S-7</th>
<th>S-8</th>
<th>S-9</th>
<th>S-10</th>
<th>S-11</th>
<th>S-12</th>
<th>S-13</th>
<th>S-14</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>1.67</td>
<td>1.57</td>
<td>1.61</td>
<td>1.73</td>
<td>1.91</td>
<td>1.97</td>
<td>2.03</td>
<td>2.04</td>
<td>2.09</td>
<td>2.13</td>
<td>2.15</td>
<td>2.18</td>
<td>2.21</td>
<td>2.24</td>
</tr>
</tbody>
</table>

Fig. 3. Comparison of the results

6. Conclusions

Performed calculations yield the following conclusions:

– in Figure 3 we observe that the choice of the presented method of calculations has a large impact on the value of the $c_f$ coefficient for individual sections of the analyzed tower structure;

– analyses of towers of high complexity with the combination of flat-sided and circular-section members, containing feeders and ladders, antennas and their support structures, should be based on the method for special cases;

– formulae adopted in this method have been introduced into standard [1] to cover any combination of flat-sided or circular section members along with a shielding factor;

– determination of the wind drag coefficient with respect to the incorrect calculation approach can lead to the overestimation of the mean wind value, which has crucial impact on the results of analyses of the carrying capacities of existing and new structures;

– the results that have been obtained according to the method for special cases correlate well with the ones presented in publication [3];
– considering aerodynamic behavior of tower structures, it is worth underlining that the full-scale measurements (given by Nielsen in [7]) showed that the wind resistance of lattice towers should be significantly lower than the estimated ones conducted according to standards [1, 4].

References


Obciążenie odcinkowe na kierunku działającego wiatru określone jest natomiast jako (5). Jednym z parametrów niezbędnym do określenia wielkości oddziaływania wiatrem jest właśnie współczynnik oporu aerodynamicznego, którego wartość determinuje wielkość tego rodzaju obciążenia.

3. Analizowana konstrukcja

4. Obliczenia oporu aerodynamicznego
Wszystkie kalkulacje oparte są na jednym z najbardziej istotnych parametrów w teorii oporu aerodynamicznego konstrukcji szkieletowych – współczynniku wypełnienia (8). Tabela 3 prezentuje pola powierzchni całkowitych poszczególnych segmentów wieży. Wykorzystując normę [1], a także rekomendacje zawarte w [3], obliczenia zostały wykonane przy zastosowaniu dwóch niezależnych podejść, które zależą od rodzaju konstrukcji: symetrycznej z ograniczonymi elementami wyposażenia lub z pełnymi elementami wyposażenia, tj. drabiną, pomosty itp. W celu prezentacji wyników, a przede wszystkim algorytmu obliczeniowego wybrano segment 10 wieży.

4.1. Całkowity współczynnik oporu aerodynamicznego – metoda ogólna

4.2. Całkowity współczynnik oporu aerodynamicznego – metoda dla przypadków specjalnych
Zależność opisującą całkowity współczynnik oporu aerodynamicznego zgodnie z [1] przedstawiona została w (17). Główną różnicą pomiędzy prezentowanymi w niniejszym opracowaniu metodami (ogólną i dla przypadków specjalnych) jest traktowanie segmentu konstrukcji wieżowej jako całości bez podziału na konstrukcję i elementy wyposażenia w drugim podejściu obliczeniowym. W metodzie dla przypadków specjalnych bierzemy pod uwagę oprócz ściany 1 (metoda ogólna) również ściany 2 i 3 opisane na rysunku 2. Uwzględniamy poza tym efekt przesłaniania elementów konstrukcji używając w analizie współczynnika przesłaniania zdefiniowany w (18).

W tabeli 4 w sumie zebrano wszystkie obliczeń niezbędne do określenia oporu aerodynamicznego. Dla segmentu S-10 wartość współczynnika siły opisana jest w (20). W tabeli 5 zebrano wyniki dla pozostałych segmentów wieży.

5. Porównanie wyników
Porównanie wyników uzyskanych na podstawie dwóch niezależnych procedur normowych zaprezentowano w formie graficznej na rysunku 3.

6. Wnioski
Przeprowadzone analizy pozwalają na przedstawienie następujących wniosków:
– na rysunku 3 możemy zaobserwować, że wybór metody obliczeń w znacznym stopniu determinuje uzyskane wyniki współczynnika $c_f$,
– analizy konstrukcji wieżowych o znacznym stopniu złożoności, z elementami konstrukcyjnymi wykonanymi z elementów okrągłych i płaskich, wyposażonymi w kable, drabiny wiażowo–kable, anteny i ich konstrukcje wsporcze powinny zostać przeprowadzone zgodnie z założeniami metody dla przypadków specjalnych,
– formuły obliczeniowe wyżej wymienionej metody wprowadzono w normie [1],
– określenie współczynnika oporu aerodynamicznego konstrukcji wieżowej na podstawie niepoprawnej metody obliczeniowej może prowadzić do przeszacowania wielkości oddziaływania wiatrem, co w przypadku analiz nośności istniejących konstrukcji może prowadzić do błędnych wniosków i zaleceń,
– rezultaty w przedstawione w analizach otrzymano stosując metodę dla przypadków specjalnych i korelują z wynikami zaprezentowanymi w [3],
– rozważając aerodynamikę konstrukcji wieżowych, warto podkreślić, że pomiary dla konstrukcji w skali naturalnej [7] udowodniły, że opór aerodynamiczny wieżowych konstrukcji kratowych może być znacznie mniejszy niż ten określony na podstawie norm [1, 4].