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The reasons for hybrid light pole failures – an analytical study

Analityczne badania przyczyn uszkodzeń hybrydowego słupa oświetleniowego

Abstract

This paper presents the results of a durability analysis of a hybrid light pole. The developed model includes a supporting structure of a pole with photovoltaic panels, a wind turbine and a boom with a light case. Due to various operating conditions, these poles may be characterised by a different configuration of the mutual spatial distribution of individual components. This results in a large diversity in the analysis results, hence the fact that the research was performed for the selected configuration variant for which the most unfavourable operating conditions were forecasted. In order to reveal potential stress concentration areas, a series of structural analyses was applied using the finite element method. As part of the work, changes to the supporting structure of the pole were proposed and to confirm the possibility of improving the resistance of the structure, additional analyses were conducted.

Keywords: finite element method, hybrid light pole, modal analysis, response spectrum analysis

Streszczenie

W pracy przedstawiono wyniki modelowych badań wytrzymałościowych hybrydowego słupa oświetleniowego. W opracowanym modelu uwzględniono konstrukcję nośną słupa wraz z panelami fotowoltaicznymi, turbiną wiatrową oraz oprawą oświetleniową. Ze względu na zróżnicowane warunki eksploatacyjne słupy te mogą charakteryzować się odmienną konfiguracją wzajemnego przestrzennego rozmieszczenia poszczególnych komponentów. Powoduje to duże zróżnicowanie wyników analiz, stąd badania przeprowadzono dla wytypowanego wariantu konfiguracji, dla którego prognozowano najbardziej niekorzystne warunki eksploatacji. W celu ujawnienia potencjalnych miejsc koncentracji naprężeń zastosowano szereg analiz konstrukcji metodą elementów skończonych. W ramach pracy zaproponowano zmiany w konstrukcji nośnej słupa oraz przeprowadzono analizę potwierdzającą możliwość poprawy odporności konstrukcji.

Słowa kluczowe: metoda elementów skończonych, hybrydowe słupy oświetleniowe, analiza modalna, analiza spektrum reakcji

1. 1. Introduction

The use of stand-alone lighting poles is particularly beneficial in places where it is difficult or unprofitable to supply electricity. These poles are often described as being hybrid due to the supply of renewable energy in the form of both solar and wind.

The inspiration for addressing the problem of hybrid poles was the suggestion of one of the manufacturers. They described a situation in which a proportion installed poles were damaged in the form of fatigue cracking of the boom arm bearing element after a short period of time (Fig. 1). The attempts made by the manufacturer to improve the structure by adding a reinforcing rib, shown on the picture presented below, did not bring the desired results.

Fig. 1. Photograph of sample damage

It is interesting that this damage occurred in only a few cases. After obtaining assurance that the same production conditions were maintained for all poles, the assumption was made that the individually selected configuration of modules mounted on hybrid poles could be the cause of damage.

On the supporting constructions of such poles, in addition to the light module, photovoltaic panels and wind turbines are mounted. In reality, the configuration of these elements is different for each particular installation. Photovoltaic panels are located around the axis of the column depending on the direction of the sun's rays. However, the setting of the lighting fixture depends on the position of the lamp relative to the illuminated road (Fig. 2). For these reasons, there is a large variety of configurations of these elements. Additionally, the element which randomly changes its position around the axis of the pole is the wind turbine as it adapts to the current wind direction.

The supporting structure of the hybrid pole may be exposed to variable loads coming from the wind [9]. These loads can vary both in terms of the values of the forces and the direction of their actions. Except the variable nature of wind forces there are load changes caused by the wind-dependent position of the wind turbine.

From the point of view of the considered problem – damage to the supporting structure of hybrid poles – the dynamic properties of the object may be relevant [2]. There is a risk of resonance vibrations being activated, as a result of which, undesirable concentrations of time-

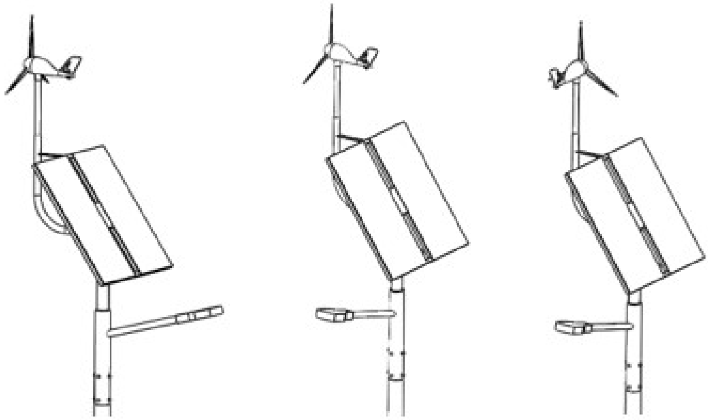

Fig. 2. Sample configurations of modules mounted on the hybrid light pole

varying stresses may occur. This may be the direct cause of fatigue damage to the supporting structure of the hybrid pole. An attempt to diagnose this problem was made using an analytical technique and finite element method.

2. Research object

The research object is a hybrid lighting pole equipped with a wind turbine located above a set of photovoltaic panels. This arrangement avoids covering the panels with a wind turbine (Fig. 3).

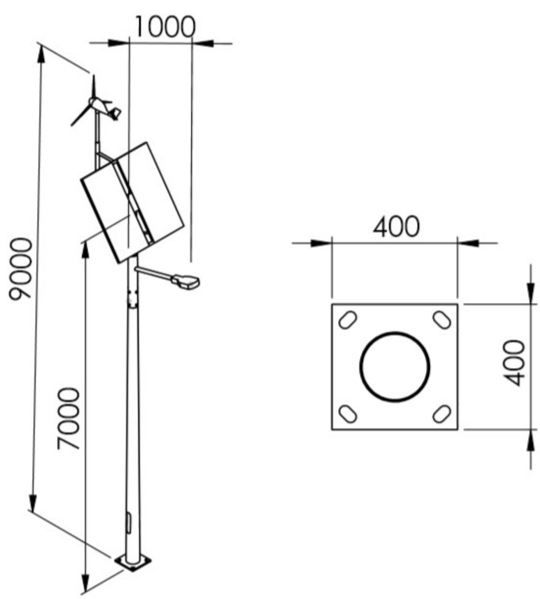

Fig. 3. Construction and dimensions of hybrid lighting pole

The set of considered configurations was analysed and configurations in which fatigue damage to the boom with the lamp occurred were selected. Fig. 4 presents the selected configuration in which the boom with the lamp is set in a plane perpendicular to the plane of the photovoltaic panel installation.

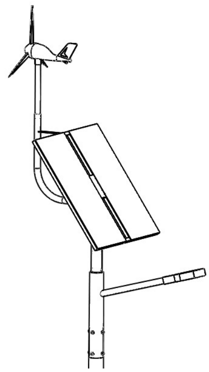

Fig. 4. Selected configuration

3. Modelling

A series of preliminary calculations were performed in the planning of the wide range of computational analysis using the finite element method (FEM). The aim of these calculations was to develop a reliable model in terms of the accepted conditions for the discretisation of the object. Due to the complex construction of the analysed object, solid elements were used for discretisation. As part of the modelling stage, analyses were conducted to examine the impact of the discretisation method on the expected results. Initially, research was conducted on the influence of the division of mesh density on the results of frequency analysis. It was decided that differences in results below 5% for individual discretisation options can be considered to be acceptable, further densification of the mesh would lead to a significant decrease in the efficiency of calculations (model with too many degrees of freedom) [5]. These conditions

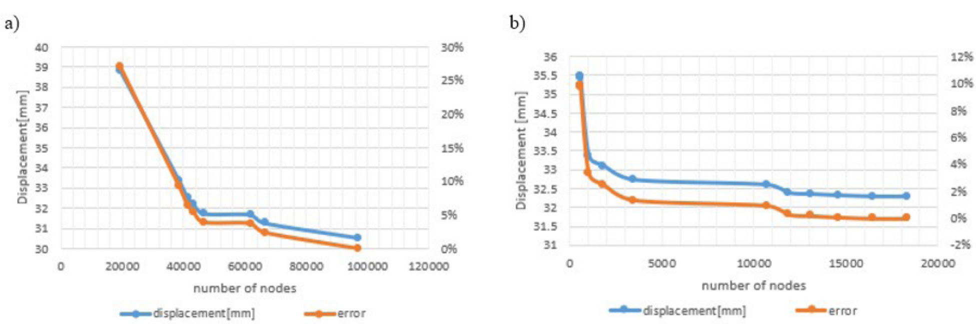

Fig. 5. Influence of mesh density on results

were fulfilled for a mesh with a number of nodes above 38,000 for the supporting structure (Fig. 5a) and for more than 11,000 for solar panels (Fig. 5b).

A mesh consisting of 3,000 nodes and 10,000 elements was used to discretise the wind turbine with the use of an automatic meshing procedure in the areas of shape change.

In the next stage of modelling, a static analysis was performed under gravitational loading in order to pre-determine stress distributions. The results of this analysis were used for manual compaction of the mesh in areas of the highest stress, so that in the indicated areas, especially in weldment joints, the elements should not be larger than 2 mm.

The final stage of the model's development was to assess the quality of the grid by determining and analysing typical mesh quality indicators, such as *aspect ratio*, *skew angle* and *warpage* [7]. The first of these determines the ratio of the shortest edge of the element to the longest edge. The aspect ratio for tetragonal and hexagonal elements is calculated respectively on the basis of the following formulas:

$$AR_T = \frac{\sqrt{3}\min(h_i)}{\sqrt{2}\max(l_i)} \qquad AR_H = \frac{\min(l_i)}{\max(l_i)} \tag{1}$$

The *skew angle* indicator is calculated by finding the minimum angle between the sections connecting the individual nodes and the centres of the opposite sides of each wall of the element. This coefficient is calculated on the basis of the following formulas:

$$SA_T = 1 - \max\left(\frac{90^\circ - \alpha_i}{90^\circ}\right) \qquad SA_H = 1 - \max\left(\frac{\left|90^\circ - \alpha\right|}{90^\circ}\right) \tag{2}$$

The last tested indicator was *warpage,* which defines the deviation of the element's walls from the planes of their best fit. This indicator is described by the following formula:

$$WA = 1 - \frac{h}{\min(l)} \tag{3}$$

	Basic model	Improved model
Hexagonal	78,291	114,669
Tetragonal	10,116	5,221
Wedge	85,015	38,512
Pyramid	73,991	58,481

Fig. 6. Final mesh model

Due to the necessity to maintain the quality of mesh in terms of meeting the abovementioned indicators [5], the grids of supporting structure elements and solar panels were compacted. As a result, a model consisting of 214,768 nodes and 247,413 elements was obtained, this model is shown in Fig. 6. With the exception of tetra- and hexagonal elements, the hexa-tetra link elements were of pyramid (5 node) and wedge (6 node) types.

The analysis of static properties performed in the first stage of research revealed two areas of intense stress concentrations. Despite low values of these stresses, their locations coincided with the indicated damage areas. Figs. 7 and 8 show areas of stress concentration revealed in the analysis of static properties.

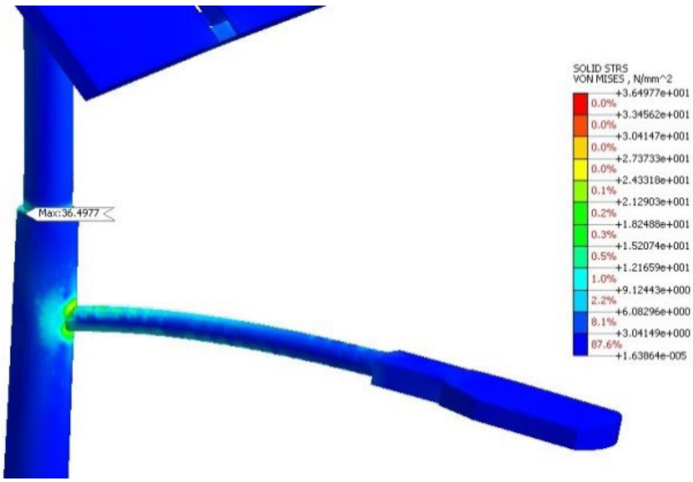

Fig. 7. Concentration of stresses caused by the force of gravity in the area of connection between the boom of the lamp and the pole

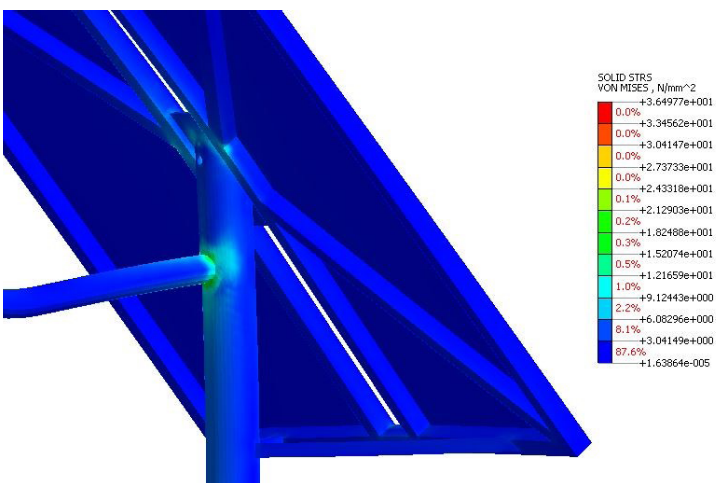

Fig. 8. Concentration of stresses caused by the force of gravity in the area of connection of the wind turbine with the pole

4. Analytical and numerical research for finding the causes of damage

Due to the complex nature of the real loads on the supporting structure of hybrid poles, the search for the causes of damage to these structures was performed in several stages. In the first stage, the analysis of the impact of wind on the supporting structure of the pole was conducted. In this analysis, the distribution of pressure acting on the surfaces of all elements of the object was determined. This distribution was used as an external load in the analysis of static properties. In this analysis, appropriate stress distributions were determined. In the next step, a modal analysis was performed to determine the dynamic properties of the object. Using the results of the modal analysis, the response spectrum analysis was then conducted, which enabled obtaining the proper distribution of stresses derived from dynamic loads. Finally, an analysis of the frequency response with the load from a working wind turbine was performed.

4.1. The impact of wind

In the current regulations, the impact of wind should be taken into account on the basis of the analytical relationships contained in official specifications [4]. Conducting analyses on the basis of this standard requires knowledge of many factors concerning, for example, exposure and topography. These regulations enable the calculation of the pressure of wind depending on the height above ground and pressure resulting from a snow load. The information provided from the manufacturer shows that during the operation time when the destruction of the structure occurred, there was no snowfall. For this reason, calculations of loads resulting from snow were omitted in further analyses. The expected average pressure was approximately calculated using formulae:

$$q(z)=\delta\cdot\beta\cdot f\cdot c_e(z)\cdot q(10)\left[\frac{N}{m^2}\right]$$

where δ is the factor relating to the column size (for $h\approx 8.5m$, $\delta=0.915$), $\beta\approx 1.31$ is the factor for the dynamic behaviour, $f=1$ is the factor related to topography, $c_e(z)$ is the factor dependent on the terrain of the site and the height above the ground (z), $q(10)$ is the reference wind pressure, which accounts for the geographical location of the column. Due to the fact that the pressure values determined on the basis of the standard are between 500 and 560 N/m^2 at a height of up to 6 m (below solar panels) and are close to those determined on the basis of numerical analysis, load conditions on the entire column were determined using numerical simulation.

During the maintenance of hybrid poles, extreme weather conditions were not recorded. Therefore, for the purposes of this analysis, it was assumed that objects were exposed to difficult wind conditions with wind speeds of up to 26 m/s [1]. Wind analysis was performed in the Fluid Mechanics Calculation (CFD) module of the Midas NFX program [7]. In order to determine the pressure distributions acting on the surfaces of the column elements, the air flow was simulated. Fig. 9 shows the directions of wind streams acting on the object. Analyses for wind blowing in directions perpendicular (X-axis) and parallel (Z-axis) to the considered configuration of photovoltaic panel settings and the boom with the lamp were conducted.

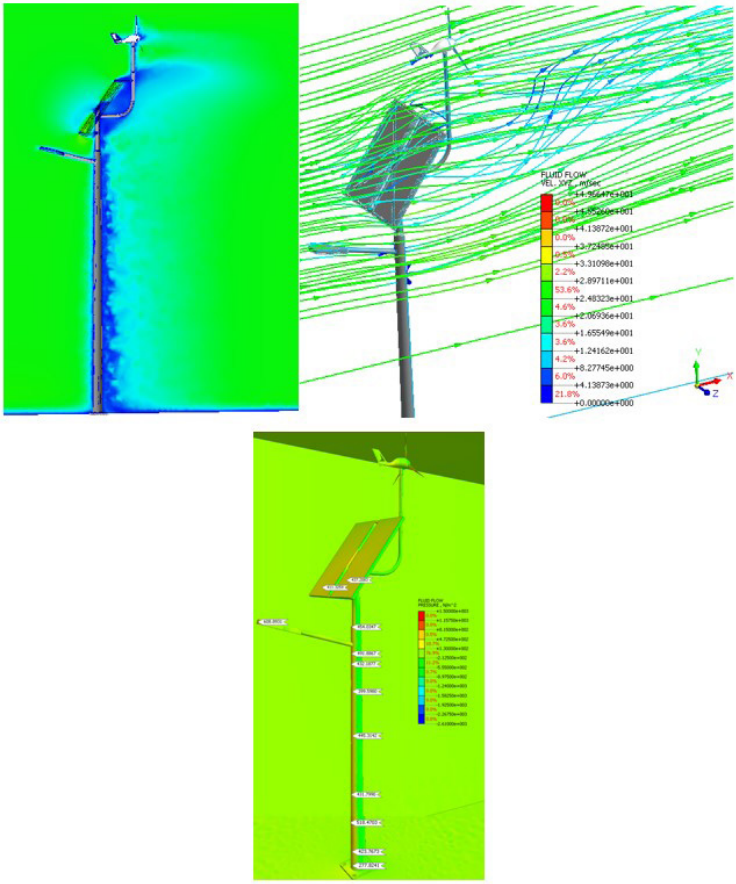

Fig. 9. Wind flow in the X direction around the pole and stress distribution obtained as a result of the flow analysis

The pressure distributions obtained as a result of the flow analysis were transformed and, as appropriate, introduced as an external load for analysis of static properties. Two analyses of these properties were conducted for the conditions corresponding to the wind load blowing from two mutually perpendicular directions (X axis and Z axis). These analyses included both loads from wind and gravitational forces. As a result there were received distributions of stresses.

Evaluation of the results of these analyses enabled areas of the concentration of stresses to be identified. Fig. 10 presents potentially dangerous places of stress concentration, from the point of view of construction durability. These places are the supporting structure of pole, the combination of the lamp module with the column and the place where the wind turbine module is connected to the column. According to the authors of work [3], the maximum stresses caused by wind influence appear in the column base plate, similar results were obtained for the considered construction. In the considered case, the failure did not occur in the area of the column base, hence the need for further analysis to be performed.

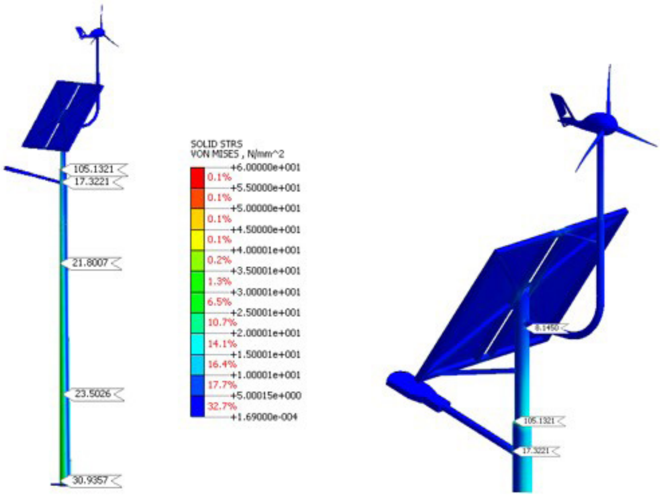

Fig. 10. Stress concentration areas due to wind loads

4.2. Modal analysis

In the next stage of searching for the causes of damage to the structure of the hybrid pole, modal analysis was performed. This analysis is commonly used to study the dynamic properties of mechanical structures. As a result of this analysis, it is possible to obtain a modal model describing a mechanical structure consisting of a set of figures and the natural frequency of vibrations. With knowledge of these characteristics, it is possible to predict the behaviour of the structure for any excitation frequencies. This analysis is one of the simplest tools used to analyse and then modify the structure in order to adjust its dynamic characteristics. It is often the first step for further dynamic analysis. The work involved a modal analysis of the structure taking into account the conditions for fixing the column to the ground.

The cumulative sum of effective masses should be between 80% and 90% in each direction of the response (Fig. 11) [8]; therefore, the modal analysis was performed for the first 50 natural frequencies, i.e. for the range 0–350 Hz.

In the case of the analysed object, this value is in the range of 0–30 Hz in the directions of the X axis and the Z axis. Therefore, the analysis was limited to the first ten natural frequencies (Fig. 13), from which Fig. 12 presents selected mode shapes. These mode shapes are interesting considering the column destruction areas.

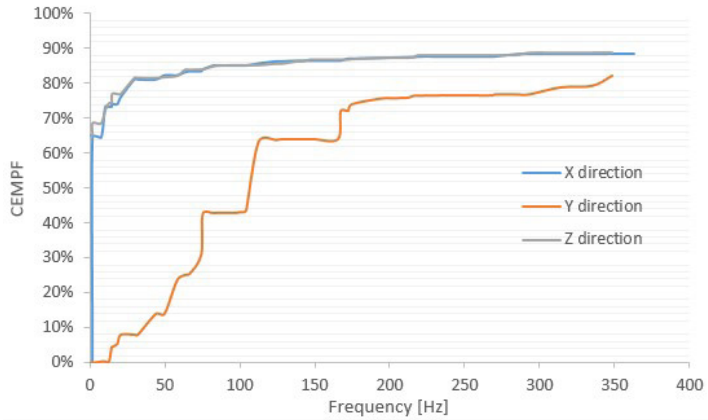

Fig. 11. Graph of the cumulative mass participation

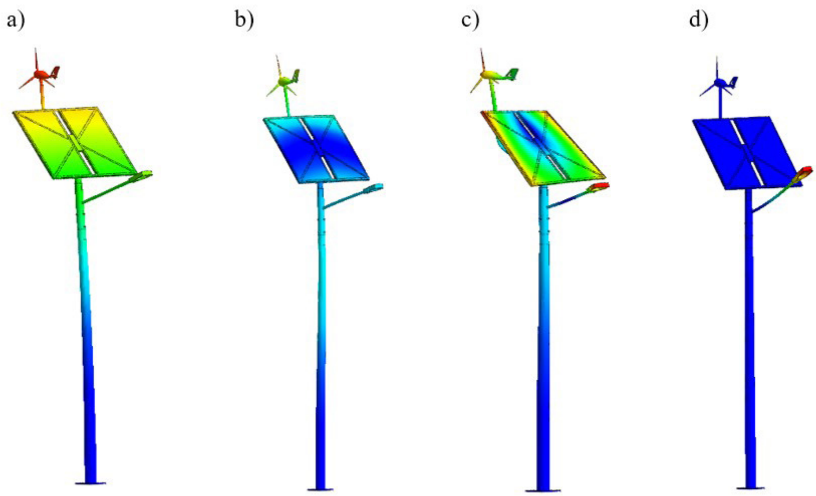

Fig. 12. Selected modes: a) mode 1 – 1.7 Hz, b) mode 4 – 9.4 Hz, c) mode 6 – 12.7 Hz, d) mode 7 – 13.2 Hz

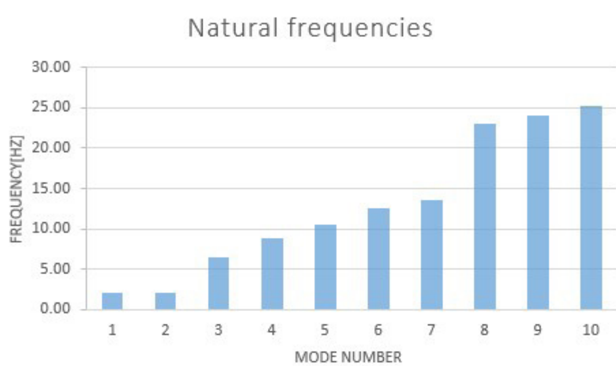

Fig. 13. Natural frequencies

The largest mass ratio (about 65%) in the X direction occurs at 1.68 Hz and in the Z direction at 1.72 Hz. However, in the X direction of frequency, the largest participation of masses (11% and 19%) are much higher, amounting to 82.3 Hz and 124.2 Hz. Modal analysis, in this case, does not directly give results that can be used to indicate the reasons for the considered damage to the hybrid poles, but it is necessary for further stages of searching for the causes of damage.

4.3. Response spectrum analysis

In the next stage of the research, the spectrum of response was analysed. This analysis is used for random frequency excitation simulating variable wind, earthquake or ocean wave loads. In the studied case, the cause of such a variable load is the impact of wind. Assuming that the resonating system can be described by a harmonic oscillator with one degree of freedom characterised by parameters relating to mass, stiffness and damping. However, the response of a system with several degrees of freedom may be a combination of responses of oscillators with one degree of freedom. When the excitation frequency is equal to the resonant frequency, the system response is only controlled by a damping factor. Using this principle, a spectrum of responses can be built [6] by registering responses in the form of displacements, velocities and accelerations for individual oscillators with appropriate dynamic loads. Spectrum is created by interpolation and using several available algorithms that allow interactions between modes to be taken into account, the most common of which is the SRSS algorithm (square root of sum of squares). The spectrum thus created is available in the Midas NFX program [7] in a module designed for fatigue strength analyses. A norm is available for structures located in Europe. Using the spectrum available in the norm, the system has been loaded with X, Y and Z forces. The last element is to take into account damping in the system. It is recommended to determine the attenuation coefficient on the basis of experimental studies; however, if this

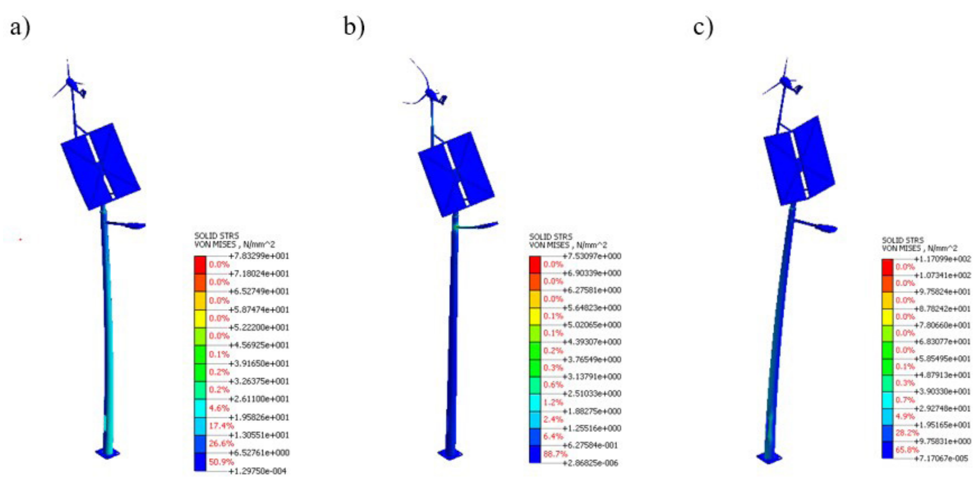

Fig. 14. Distribution of stresses for random force in the directions a) X, b) Y, c) Z

is not possible, a damping of 2% is suggested. As a result, stress distribution was obtained for the load in the directions indicated (Fig. 14).

Response spectrum reaction analysis indicated that, due to the purpose of the analyses, the area of stress concentration in the Y direction is particularly interesting despite the higher values of stresses determined in the X and Z directions. These stresses are concentrated at the welded joint of the boom of the luminaire with the column supporting structure (Fig. 14b) where the area of the damage occurred. This is the reason to search for additional factors that can cause damage. It can be assumed that they may be caused by external loads caused by the working wind turbine.

4.4. Analysis of the impact of a working wind turbine

According to catalogue data, the turbine operates at wind speeds between 2 m/s and 18 m/s, which means that the excitation frequencies are in the range of 8–23 Hz. Therefore, an additional dynamic analysis was performed in which the effect of rotational force at the wind turbine mounting site was simulated. For the adopted frequency range (8 to 23 Hz), maximum displacement functions were determined (Fig. 15).

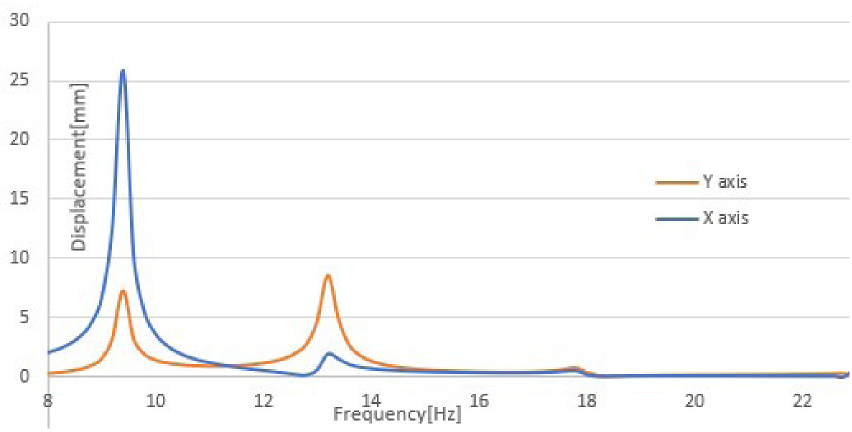

Fig. 15. Maximum displacement function for dynamic analysis with forces from wind turbine

In Fig. 15, it can be seen that the resonance of the system appears in the range of excitation frequencies, at a frequency of around 9 to 13 Hz. This indicated a significant displacement of the light arm boom in the X and Y direction due to the working turbine. This analysis confirms the assumption that the source of damage to the structure in the area of connection the light arm boom to the supporting structure of the pole could be the wind turbine.

The variable stress distribution revealed by dynamic analysis has a significant influence on the fatigue damages of the pole. Constant and variable small loads in a given direction cause may cause weakening of the structure in this area and as a result – its damage. This situation occurred in the considered construction. The columns were breaking at the connection point of the light arm boom with the supporting structure.

5. Structural modifications

The obtained results enabled proposing a structural change consisting of strengthening the place of connecting the light arm boom to the supporting structure of the pole by means of additional reinforcing ribs (Fig. 16).

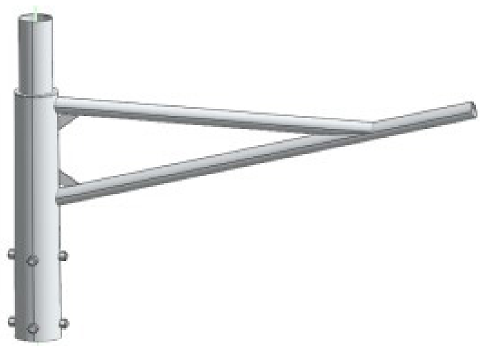

Fig. 16. Strengthening the structure in the place where the light arm boom is connected to the supporting structure of the column

The changed construction was re-examined. The results obtained showed slightly smaller values of maximum stresses but a significantly favourable change in stress distribution (Fig. 17). This stress distribution reduces the likelihood of structural damage. Such an approach reduces the likelihood of structural failure in the considered area of the structure.

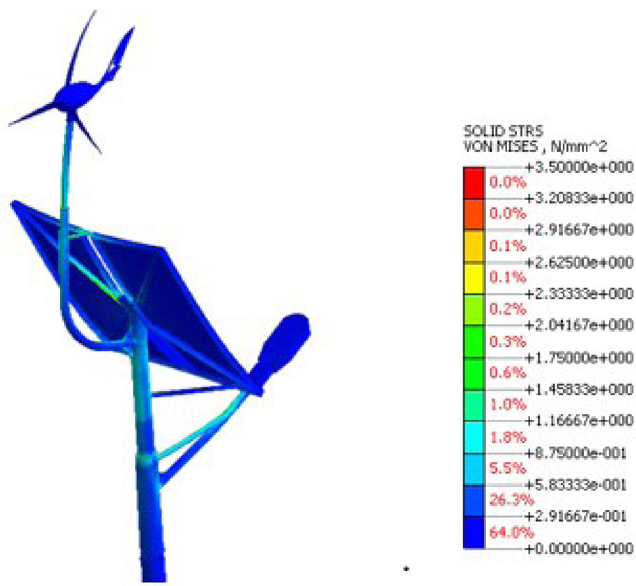

Fig. 17. Distribution of stresses in the reinforced structure

6. Conclusions

The procedure for analysing the structure of a hybrid pole described in the article made it possible to reveal the causes of damage in the area of the connection of the light arm boom to the supporting structure of the pole. Based on the results of these analyses, a fairly simple and low-cost construction change was proposed that would significantly reduce the possibility of damage in the studied area. On the basis of information received from the manufacturer, it can be concluded that the strength of the structure under operating conditions can be increased. At the time of writing, no further damage had been found. This confirms the effectiveness of the use of structural analysis in the design of structures such as hybrid lighting poles.

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