ДГКС
Друштво грађевинских
конструктера Србије

ASES
Association of Structural
Engineers of Serbia

R-35

Kongres 2022
Congress 2022

Miroslav Marjanović[1], *Marija Milojević*[2], *Miloš Jočković*[3]

SPECIFIČNOSTI PROJEKTOVANJA ANEMOMETARSKIH ČELIČNIH JARBOLA U REPUBLICI SRBIJI

Rezime:

Projektovanje i izgradnja velikih vetroparkova zahteva prethodno merenje vetroenergetskog potencijala na predmetnoj lokaciji. Za ove potrebe, koriste se anemometarski čelični stubovi (jarboli) koji nose opremu za merenje brzine i pravca vetra na različitim visinskim novoima. U ovom radu biće prikazane neke specifičnosti u analizi, konstrukcijskom oblikovanju, fundiranju i montaži čeličnih jarbola, uočene tokom projektovanja (od strane autora) i izgradnje više ovakvih konstrukcija u Republici Srbiji u poslednje tri godine.

Ključne reči: čelični jarbol, Evrokod, nelinearna analiza, segmentno opterećenje

IMPORTANT ASPECTS IN DESIGN OF ANEMOMETRIC STEEL MASTS IN THE REPUBLIC OF SERBIA

Summary:

Design and construction of large wind farms requires preliminary measurement of wind energy potential at the future wind farm location. For these purposes, anemometer steel guyed masts are used, which carry equipment for measuring wind speed and direction at different altitudes. This paper will present some important aspects in the analysis, structural design, foundation and assembly of steel masts, identified during the design (by the authors) and construction of several such structures in the Republic of Serbia in the last three years.

Key words: steel mast, Eurocode, nonlinear analysis, wind patch loads

---

[1] *Assistant professor, Faculty of Civil Engineering, University of Belgrade, Serbia, mmarjanovic@grf.bg.ac.rs*
[2] *Assistant, Faculty of Civil Engineering, University of Belgrade, Serbia, mmilojevic@grf.bg.ac.rs*
[3] *Assistant professor, Faculty of Civil Engineering, University of Belgrade, Serbia, mjockovic@grf.bg.ac.rs*

1. INTRODUCTION

Due to the increasing demands of modern industry concerning communication and energy, the design and construction of large wind farms have been conducted in Serbia in the last 15 years. This required a preliminary measurement of wind energy potential at the future wind farm location. For carrying equipment for measuring wind speed and direction at different altitudes, guyed lattice steel masts are usually used. They are very slender and tall structures, consisting of a vertical central mast laterally supported at several levels along its height by sets of inclined pre-tensioned guy ropes. Due to the required lifespan, the number of collapses of masts is relatively far greater than for other types of structures [1].

The optimal design of a guyed mast requires a series of iterations between the conceptual design and the structural analysis. It is relatively hard to give a precise height above which the guyed mast is an optimal structural solution. This depends on factors such as land cost for the specific location, but quite often the guyed masts are used for heights above 60-80m.

The central mast usually consists of:

- the base segment, forming a fixed or pinned connection with the foundation,
- the main part, consisting of a number of standard segments, each usually 3.00m long, and
- the last segment, usually carrying a measuring device and lightning rod.

The standard segment is a spatial lattice structure, usually of triangular leg layout and side length varying between 0.45-0.90m. It comprises leg members and horizontal and diagonal elements welded to the leg members. The connection between the segments is made through the bearing plates. Due to the dynamic nature of wind loading, prestressed bolts with full prestressing forces are used (see Figure 6d).

Figure 1 - Installed guyed masts of 120.78m, 160.00m and 126.30m height, respectively (source: NETInvest Engineering and Consulting Solutions)

The anemometric masts do not require big and heavy frame sections due to the very small dimensions and weight of the attached equipment. Consequently, these structures are lighter than other mast types (i.e. for telecommunication purposes), and the standard segments can be easily manipulated, lifted and connected to one another [2-4].

This paper presents some important aspects of structural analysis, design, foundation and execution of temporary steel anemometric masts, identified during the design (by the Institute of Numerical Analysis and Design of Structures - INP) and construction of four such structures in the Republic of Serbia in the last three years (see Figure 1).

2. CONSIDERED GUYED MAST STRUCTURES

In the last three years, four guyed mast structures have been designed or validated by the INP. The main properties of the considered structures are given in Table 1, while the schematic layout of the structures and their cross sections of the mast shaft are illustrated in Figure 2.

Table 1 - Properties of the considered guyed mast structures

#	Height	$v_{b,0}$	Ice class	Steel	Leg members	$N_{b,Rd}$	m
1	120.78 m	21 m/s	ICG-3	S275	∅50×4mm	159 kN	26 kg/m
2	141.30 m	25 m/s	ICG-2	S355	∅40mm (full)	300 kN	54 kg/m
3	126.30 m	25 m/s	ICG-2	S355	∅40mm (full)	300 kN	54 kg/m
4	160.00 m	32 m/s	ICG-2	S355	∅88.9×6.3mm	571 kN	62 kg/m

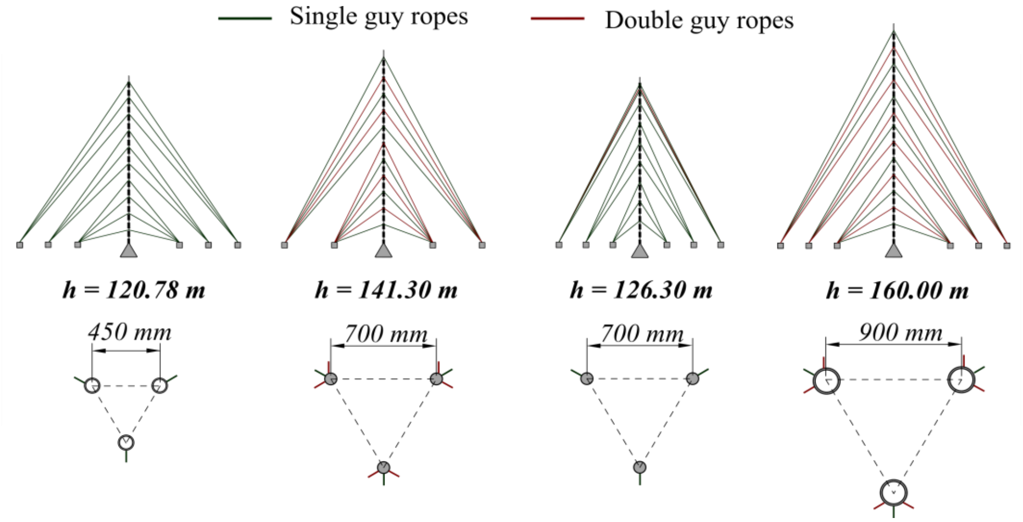

Figure 2 - Schematic layout and cross-sections of the considered mast structures

It should be pointed out that structures 1-3 have been designed (validated) based on the existing structural solution of the mast shaft. In these cases, the layout of the cables, foundation solution and complete structural validation according to SRPS standards was done by the INP, but without the possibility to change the steel grade, members and detailing of the mast shaft. In structures 2-3 illustrated in Figure 2, the leg members are full circular sections, which generate lower wind load on the mast shaft, but have lower flexural buckling resistance $N_{b,Rd}$ in comparison against CHS, according to SRPS EN 1993-1 [5].

Based on the experience gained through design validation of structures 1-3, a 160.00m guyed mast was entirely designed by the INP, including the layout, complete structural detailing and foundations in 2020.

Obviously, all considered structures had a triangular layout of leg members of the mast shaft. This layout has an advantage against the square layout by means of lower wind incidence factor K_θ and lower wind force coefficients $c_{f,s,0}$, according to Section B.2.2. of SRPS EN 1993-3-1 [6]. Consequently, it induces lower wind forces on the the mast structure.

All members of the mast shaft are circular (full or hollow section). The flat members should be avoided because their drag (pressure) coefficients are more than twice higher when compared against the circular members. Finally, the discrete ancillary items on the structure are almost negligible, and their area A_A was adopted as 10-20% of the structural area A_s.

In all cases, guy ropes were made of galvanized steel with a tensile strength of 1770 N/mm^2, type 6×19+FC, with a minimum breaking force extracted from [7]. When selecting the guy layout, several important aspects should be taken into account: (i) number of guy levels, (ii) number of guys per guy level, (iii) distance between the adjacent guys, (iv) guy lengths and (v) guy diameter and material properties. These factors influence the decision whether the equivalent static analysis may be performed, which is quantified through the factor β_s, according to [6]. In all considered structures, the dominant selected guy distance was 12m.

The number of guys per guy level is also important for preventing the torsion of the mast shaft. The preferred solution by the authors is to use alternately the guy levels with 3 and 6 guys per level, respectively. The cables are attached to concrete blocks, radially distributed around the mast shaft in several concentric circles (where the diameter of the outer circle is approximate to the mast height). This solution requires 6 concrete blocks per circle (Figure 2), and more guys to be attached to the mast shaft, when compared with the classical solution of 3 guys per level along the entire mast shaft and thus 3 concrete blocks per circle (3×120^{o} layout).

The proposed solution, successfully applied in the 160.00m mast, prevents the mast's torsion and provides a more uniform distribution of the forces in the guys. The maximum forces in the guys are proportionally lower, leading to the easier anchorage of the guys to both the mast shaft and the concrete blocks. Anchoring details are given in Section 5.

The mast is supported by a central RC foundation, which is usually square, due to the simple solution for the reinforcement and formwork. Of course, the symmetry of the structure implies that a circular central foundation may be used.

3. STRUCTURAL ANALYSIS

Steel lattice masts are slender and vulnerable structures. Structural analysis of a guyed mast is thus complex due to the geometrically nonlinear behaviour of the structural system and the random nature of the wind loads. Geometrically nonlinear analysis was performed with P-Δ effects, and all load combinations were constructed as independent load cases without the superposition principle.

The masts were modeled in SAP2000 [8], based on the finite element method, as an equivalent spatial beam structure, supported by guys at different altitudes. The initial prestressing forces were assigned to the cable elements. According to EN1993-1-11 [9], the catenary effect was taken into account by applying an effective modulus of elasticity for guys, E_t=130GPa (combinations without ice load) and E_t=121GPa (combinations with ice loads), according to the following formula:

$$E_t = E \Big/ \left(1 + \frac{w^2 \cdot l^2 \cdot E}{12\sigma^3}\right) \tag{1}$$

where: E = 165 GPa is the elasticity modulus of the guy; w is the guy unit weight; l is the guy length σ is the stress in the guy.

Based on the obtained member forces, the ultimate limit state (ULS) and stability checks of all structural members were performed according to [6, 7], while the joints calculation was performed according to [10].

The serviceability limit state (SLS) was checked according to SRPS EN1993-1-11 [9] to provide the elastic service conditions by limiting strains in cables. In that manner, corrosion control measures were not affected and the fatigue design was catered to uncertainty. The stress in cables was limited to $f_{SLS} = 0.50\ \sigma_{uk}$, where $\sigma_{uk} = F_{uk}/A_m$, and A_m is the area of the metallic cross-section and F_{uk} is the minimum rope braking force.

Finally, leg members were controlled against the fatigue effects according to [11].

4. ACTIONS ON THE STRUCTURE

The characteristic values of the actions were calculated in accordance with a set of Eurocode-based SRPS standards [5-7, 9-15] and the relevant ISO standard [16] for determining ice loading. The design values of the actions were determined according to the load combinations defined in [6, 12]. The following loads were considered: (i) self-weight and additional dead load, (ii) cable pretension forces, (iii) ice load, (iv) wind action and (v) seismic actions. The snow and temperature effects were neglected.

Few computer programs are available for a complete dynamic stochastic analysis of guyed masts. Therefore, considerable efforts were spent in producing simplifications for the design rules for codes and standards. Relatively reliable simplified procedure was developed and adopted SRPS EN1993-3-1 [6]. The procedure is based on simplified static patch wind models. According to [6], 3 criteria must be satisfied to ensure that the equivalent static analysis of the guyed mast can be performed. A check of these conditions showed that equivalent static analysis might be applied for all considered mast structures.

4.1. VERTICAL ACTIONS AND CABLE PRESTRESSING

The self-weight was assigned automatically. The additional dead load originates from the equipment on the mast according to the manufacturer's specification. Initial prestressing forces were assigned in cable elements using SAP2000. They were adopted in the range 10-20% of the minimum rope braking force, according to [7].

The effect of ice on the structure has been investigated by many authors [17]. It was calculated according to [16], for considered glaze ice-class (ICG), and assigned as equally distributed vertical loading to the mast and guys.

4.2. WIND ACTION

The lattice masts are sensitive to the dynamic action of the wind. Ice on a mast will by its weight change the dynamic behaviour, as well as it may increase the wind drag of a lattice mast dramatically. Therefore, it is essential that masts are analyzed for the dynamic response to the wind [1]. Therefore, the wind resistance of the structure must be accurately determined, including its ancillaries such as ladders and cables.

Wind loads on the mast structure should be calculated according to the fundamental wind velocity $v_{b,0}$, and the appropriate terrain type and orography factor c_o according to [13]. The design value of wind load on a mast with a triangular layout of leg members should be calculated for three characteristic wind directions: +Y, -Y and X, see Figure 3.

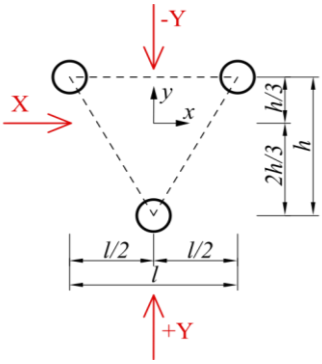

Figure 3 - Considered wind directions

The total wind effect on the structure should be calculated as a sum of equivalent static action of the *mean wind* load, corresponding to a 10-minute mean wind velocity in the direction of wind action, and fluctuating load due to wind gusts (*patch wind load*). For the sake of simplicity, a mean wind can be modelled as a uniformly distributed load along the considered mast segment, where the reference height z is the height of the top of the segment. Mean wind load to the guys lies in the plane defined by the considered guy and the considered wind direction. For the sake of simplicity, a uniform load distribution along the guy may be used, with $q_p(z)$ determined for $z=2H/3$ (H is the height of the guy attachment to the mast).

Successive patch wind loads should be assigned to the mast sections as follows: (i) on each span of the mast between adjacent guy levels, including the span from the base of the mast to the first level of the guy and the cantilever, (ii) from mid-point to mid-point of adjacent spans, (iii) from the base of the column to the mid-height of the first level of guys, and (iv) from the middle of the height of the span between the penultimate and the top guy level, if there is no cantilever present, or including the cantilever if relevant. The patch load on the guys should be applied within the same boundaries, perpendicular to each guy, in the plane containing the guy and the wind direction. For simplification, the patch loading may be smeared over the whole height of the relevant guy by multiplying the wind load with the ratio z_p/z_G, where z_p is the height of the patch on the guy and z_G is the height to the attachment of the guy to the mast.

As the superposition principle is not valid, forces due to the patch loads $S_{p,Li}$ should be obtained as the difference of: (1) forces due to the sum of the mean wean load and i^{th} patch wind load, and (2) forces due to the mean wind load only. The total effect of wind fluctuation (patch load), S_p, should be obtained by combining the individual effects of all patch loads as:

$$S_P = \sqrt{\sum_{i=1}^{N} S_{pLi}^2} \qquad (2)$$

where N is the total number of patch load cases. The overall effect on the structure, which introduces the effect of wind fluctuation, is equal to the envelope of the following loads:

$$S_T = S_M \pm S_P, \tag{3}$$

where S_M is the effect of mean wind load, while S_P is the effect of patch load.

4.2.1. The effect of atmospheric icing combined with the effect of wind

The icing of the mast significantly increases the structure's weight, while the thickness of the ice increases the surface of the structural elements exposed to the wind. Therefore the wind force on the structure increases, which may have a very adverse effect on the mast. The calculation of the wind effect is the same as for the ice-free structure, with the changes in the thickness of the structural elements and appropriate drag coefficients. The ice may completely block the structure if masts are located in areas where severe atmospheric icing occurs.

The effects of ice and wind are combined in two ways:

- Dominant wind (high probability of occurrence) + associated ice (low probability),
- Dominant ice (high probability of occurrence) + associated wind (low probability).

Due to the low probability that a 50-year wind and high ice will occur simultaneously, a coefficient k, which reduces the wind pressure on the iced structure, is introduced in [16].

4.3. LOAD COMBINATIONS

According to SRPS EN1990 [12] and SRPS EN1993-3-1 [6], taking into account the reliability class 1 (towers and masts built on unmanned sites in open countryside; towers and masts, the failure of which would not be likely to cause injury to people) and partial safety factors for actions (γ_G, γ_P, $\gamma_{Q,w}$, $\gamma_{Q,ice}$), coefficients for the combinations of variable actions (ψ_w, ψ_{ice}) and coefficient for the reduction of wind action in the combination with ice (k), the following design situations are adopted for the ultimate limit state (ULS):

$$\begin{aligned}
&\gamma_G \cdot G_k + \gamma_P \cdot P_k + \gamma_{Q,w} \cdot Q_{k,w} \\
&\gamma_G \cdot G_k + \gamma_P \cdot P_k + \gamma_{Q,ice} \cdot Q_{k,ice} \\
&\gamma_G \cdot G_k + \gamma_P \cdot P_k + \gamma_{Q,w} \cdot k \cdot Q_{k,w,ice} + \gamma_{Q,ice} \cdot \psi_{ice} \cdot Q_{k,ice} \\
&\gamma_G \cdot G_k + \gamma_P \cdot P_k + \gamma_{Q,w} \cdot k \cdot \psi_w \cdot Q_{k,w,ice} + \gamma_{Q,ice} \cdot Q_{k,ice}
\end{aligned} \tag{4}$$

In (4), G is the self-weight + additional dead load; P is the prestressing force; W is the wind on the ice-free structure; Qice is the ice loading and Qw,ice is the wind action on the iced structure. Based on the obtained results, extreme force values in structural members were determined, and their envelopes were drawn, as shown in Figure 4.

4.4. SEISMIC ACTION

Seismic action was determined using the equivalent lateral force method and multimodal analysis for the considered soil category, depending on the mast location. Elastic spectrum type, structural damping, design ground acceleration a_g and behavior factor q=1.0 are adopted according to [15]. In all cases, it was shown that the seismic action was not relevant because the maximum seismic force S_{max} is several times lower than the force due to the effect of mean wind loading $F_{m,w}$.

5. RESULTS AND GOVERNING LOAD CASES

This section briefly illustrates the envelopes of compression force $N_{c,Ed}$ distribution along the mast shaft leg members, for all considered structures. The forces are plotted in Figure 4 for the following load scenarios: maximum self-weight + prestressting of cables, maximum ice, and maximum wind load (with or without the ice effects). For all considered structures, +Y or –Y directions were the critical ones, because in these cases the greater area is subjected to wind load when compared to the X direction.

As shown in Figure 4, for the first structure validated against the ICG-3 ice class, as expected, dominant ice + associated wind was the governing load scenario. For all other structures, dominant wind + associated ice was the critical load scenario. Therefore, for the guyed masts subjected to the average ice conditions, this load scenario should be considered first in the conceptual design phase.

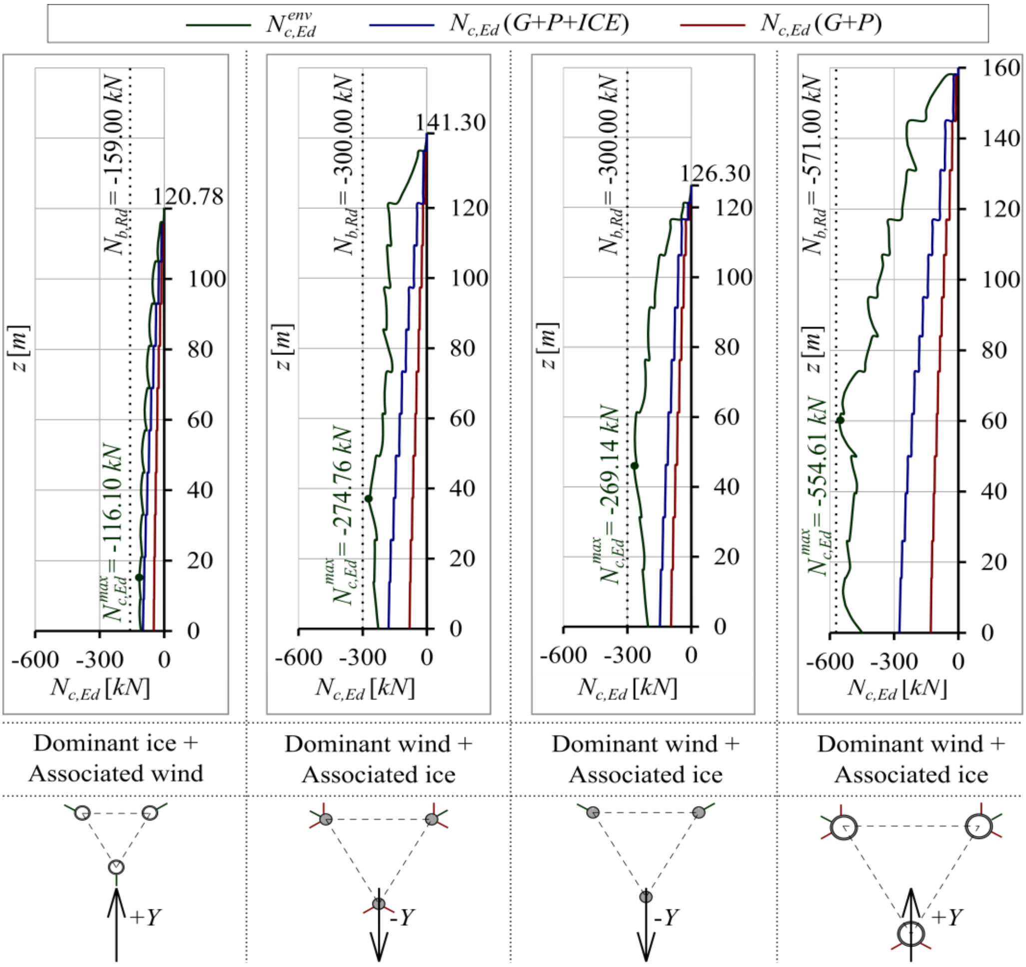

Figure 4 - Compression force $N_{c,Ed}$ distributions in leg members of the considered mast structures, with governing load scenarios and critical wind directions

6. FOUNDATIONS AND STRUCTURAL DETAILING

The important choice to be taken in the conceptual design phase is whether the mast base should be fixed or pinned to the mast foundation [1]. The authors suggest that pinned connection should nearly always be adopted for the following reasons: (i) the fixed mast base is susceptible to foundation settlement, (ii) the fixed mast base requires relatively large foundation dimensions, and (iii) the pinned connection leads to the axially loaded foundation.

There are several ways to design and execute the pinned connection between the mast shaft and the foundation. The pivoted tower base with a M30 8.8 bolt was used for the mast of 120.78m height (Figure 5a), while the tapered tower base, which is the most common solution, was used for both masts of 160.00m and 126.30m (Figure 5b-c).

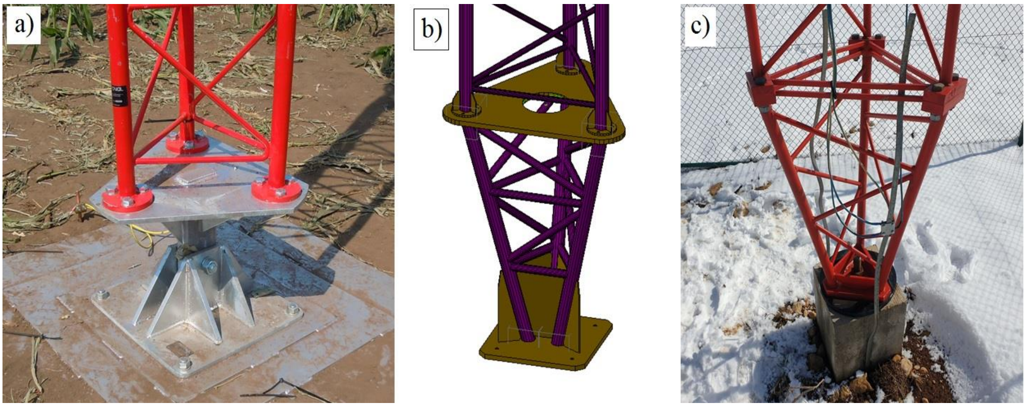

Figure 5 - First segments of installed guyed masts of 120.78m, 160.00m and 126.30m height, respectively (source: NETInvest Engineering and Consulting Solutions)

The detailing of the guy attachment to the mast (Figure 6b-c) and especially to the guy foundation (Figure 6a) is of the outmost importance, because of the relatively high forces in guys and their dynamic nature. It is essential that the guys can pivot as freely as possible under dynamic loading. In the considered mast structures, the guys were attached both to the foundation and the mast shaft using the steel bow shackles, according to SRPS EN13889 [18].

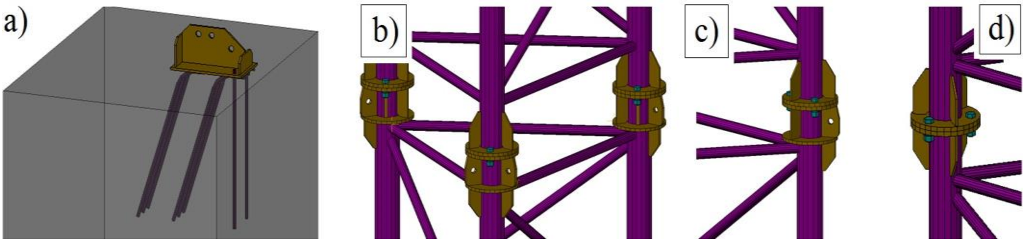

Figure 6 - a) guy anchoring system; b) segment-to-segment connection with double guy rope anchoring detail; c) single guy rope anchoring; d) standard segment-to-segment connection

According to SRPS EN1993-1-11 [9], the characteristic value of the breaking strength F_{uk} for guy ropes should be determined based on the selection of the terminations of steel wire ropes. The ropes are equipped with thimbles [19] and U-bolt grips [20], which govern the loss factor k_e to be appropriately selected when determining F_{uk}.

At the attachment of the guys to the guy foundations, an adjustable tension system should be installed to apply initial tension to the guys. Mast shaft foundations are very simple unless unusual soil conditions are encountered. The guy foundation design is governed by several limit states: sliding, overturning and uplift. In the considered structures, solid concrete blocks were used for the guy foundation, with the appropriate steel reinforcement anchorage system, shown in Figure 6a.

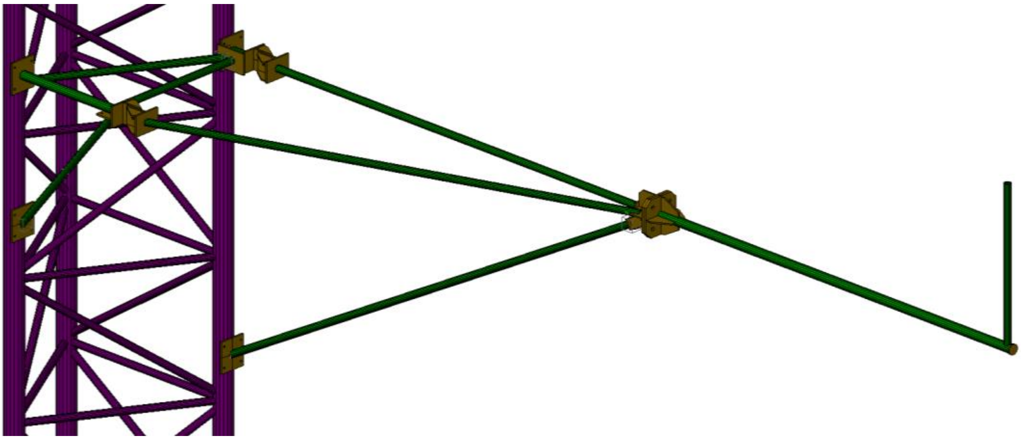

Figure 7 - Anemometer boom (green color) attached to the 160.00m mast shaft leg members

The side anemometers and wind-vanes were attached to the mast shaft on different altitudes, using the special steel booms (green color in Figure 7), constructed to be easily lifted with the mast segment and then attached to the mast in three points.

7. CONCLUSIONS

In the paper, some important aspects of structural analysis, design, foundation and execution of temporary steel anemometric masts, identified during the design and construction of several such structures in the Republic of Serbia in the last three years, have been presented. These structures are slender and vulnerable, thus requiring relatively complex geometrically nonlinear analysis with P-Δ effects. The complexity of the structural analysis is governed by the fact that all load combinations must be constructed as independent load cases without the superposition principle. For this purpose, SAP2000 was used.

Some important aspects in structural modeling and analysis were discussed, and several notes on the actions on these structures according to SRPS standards were presented. The discussion has been made on the criteria for using the equivalent static analysis instead of the dynamic analysis of the wind load influence on guyed masts.

Based on the previous experience, some important aspects in defining the proper structural layout of guyed masts were highlighted, along with the remarks of structural detailing of such structures. The importance of preventing the mast shaft torsion has been pointed out, along with the proposed solution for guy layout.

Finally, based on the results of structural calculation of several guyed masts with different guy layouts, the conclusions have been derived on the governing wind directions and load scenarios to be considered in the conceptual design phase. It was shawn that for ICG-2 ice class, dominant wind and the associated ice loading will be critical for design of leg members, while for ICG-3 the dominant ice and the associated wind will be critical.

ACKNOWLEDGMENTS

This research is carried out within the Project 200092 supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia. The research is partially financed through the Innovation Vouchers Program of the Innovation Fund of the Republic of Serbia (Voucher #1082). The authors are grateful to NETInvest Engineering and Consulting Solutions, Belgrade, for providing the photo documentation.

REFERENCES

[1] Nielsen M. G., Støttrup-Andersen U. Design of guyed masts, http://www.latensored.org/wp-content/uploads/2019/05/p_02_nielsen_andersen.pdf

[2] Jiang W. Q, Wang Z. Q, McClure G, Wang G. L, Geng J. D. Accurate modeling of joint effects in lattice transmission towers, Engineering Structures, 33 (5), 2011, 1817-1827.

[3] Zhuge Y, Mills J. E, Ma X. Modelling of steel lattice tower angle legs reinforced for increased load capacity, Engineering Structures, 43, 2012, 160-168.

[4] Erdem R. T. Analysis of guyed steel lattice mast subjected to environmental loads, Gradjevinar, 67 (7), 2015, 681-689.

[5] SRPS EN 1993-1-1: Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings, Belgrade, Serbia, Institute for Standardization of Serbia, 2012.

[6] SRPS EN 1993-3-1: Eurocode 3 - Design of steel structures - Part 3-1: Towers, masts and chimneys - Towers and masts, Belgrade, Serbia, Institute for Standardization of Serbia, 2012.

[7] SRPS EN 12385-4: Steel wire ropes - Safety - Part 4: Stranded ropes for general lifting applications, Belgrade, Serbia, Institute for Standardization of Serbia, 2009.

[8] SAP2000, Integrated Finite Element Analysis and Design of Structures Basic Analysis Reference Manual, Computers and Structures Inc. Berkeley, 1995.

[9] SRPS EN 1993-1-11: Eurocode 3 - Design of steel structures - Part 1-11: Design of structures with tension components, Belgrade, Serbia, Institute for Standardization of Serbia, 2012.

[10] SRPS EN 1993-1-8: Eurocode 3: Design of steel structures - Part 1-8: Design of joints, Belgrade, Serbia, Institute for Standardization of Serbia, 2012.

[11] SRPS EN 1993-1-9: Eurocode 3 - Design of steel structures - Part 1-9: Fatigue, Belgrade, Serbia, Institute for Standardization of Serbia, 2012.

[12] SRPS EN 1990: Eurocode – Basis of structural design, Belgrade, Serbia, Institute for Standardization of Serbia, 2012.

[13] SRPS EN 1991-1-4: Eurocode 1: Actions on structures - Part 1-4: General actions - Wind actions, Belgrade, Serbia, Institute for Standardization of Serbia, 2012.

[14] SRPS EN 1997-1: Eurocode 7: Geotechnical design - Part 1: General rule, Belgrade, Serbia, Institute for Standardization of Serbia, 2017.

[15] SRPS EN 1998-1: Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings, Belgrade, Serbia, Institute for Standardization of Serbia, 2015.

[16] ISO 12494:2017. Atmospheric icing of structures. International Organization for Standardization, 2017.

[17] Makkonen L., Lehtonen P., Hirviniemi M. Determining ice loads for tower structure design, Engineering Structures, 74, 2014, 229-232.

[18] SRPS EN 13889: Forged steel shackles for general lifting purposes - Dee shackles and bow shackles - Grade 6 - Safety, Belgrade, Serbia, Institute for Standardization of Serbia, 2009.

[19] SRPS EN 13411-1: Terminations for steel wire ropes - Safety - Part 1: Thimbles for steel wire rope slings, Belgrade, Serbia, Institute for Standardization of Serbia, 2009.

[20] SRPS EN 13411-5: Terminations for steel wire ropes - Safety - Part 5: U-bolt wire rope grips, Belgrade, Serbia, Institute for Standardization of Serbia, 2012.