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AUTOMATIZATION OF STRUCTURAL DESIGN OF ANEMOMETRIC GUYED MASTS USING SAP2000 MATLAB OAPI

Summary: This paper presents the application of a MATLAB-based framework that automates the modelling, analysis and design of anemometric steel guyed masts via the SAP2000 Open Application Programming Interface (OAPI). The design procedure is carried out in accordance with the current generation of Eurocode standards. The efficiency of the OAPI is demonstrated through the representative case study of the anemometric guyed mast structure under extreme wind and ice loads. It is shown that the developed OAPI efficiently finds the best initial mast layout according to different prescribed target objectives and comprehensibly accelerates the structural design process with minimizing the possibility of errors.

Keywords: cable, tension structures, automated structural design, OAPI-based structural analysis, nonlinear FEM

AUTOMATIZACIJA PROJEKTOVANJA ANEMOMETARSKIH JARBOLA PRIMENOM SAP2000 MATLAB OAPI APLIKACIJE

Rezime: U radu je prikazana primena aplikacije koja automatizuje modeliranje i analizu čeličnih anemometarskih jarbola, koja je zasnovana na SAP2000 Open Application Programming Interface-u (OAPI) i razvijena u MATLAB okruženju. Postupak projektovanja sprovodi se u skladu sa aktuelnom generacijom Evrokodova za konstrukcije. Efikasnost aplikacije je ilustrovana kroz studiju slučaja anemometarskog jarbola izloženog (ekstremnim) opterećenjima od vetra i leda. Pokazano je da je razvijena aplikacija u stanju da efikasno odredi optimalnu početnu konfiguraciju stuba u skladu sa različitim zadatim projektnim ciljevima, što značajno ubrzava proces proračuna konstrukcije i svodi na minimum mogućnost grešaka u projektovanju.

Ključne reči: kabl, konstrukcije sa zategnutim elementima, automatizacija projektovanja, analiza primenom OAPI, nelinearni MKE

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1. INTRODUCTION

Due to the increasing demands of modern industry for renewable energy, the design and construction of large wind farms have been extensively conducted in Serbia and the Western Balkans since the 2000s. Each wind farm project requires a preliminary assessment of wind energy potential at the proposed site. For this purpose, anemometric steel guyed masts [1] are commonly used to support equipment for measuring wind speed and direction at different altitudes. Wind-measuring equipment typically includes steel booms with side anemometers and wind vanes, which are inherently lightweight. Therefore, anemometric guyed masts do not require large and heavy frame sections and are lighter than other mast types, resulting in simplified handling and lifting and a faster erection process [2-5].

Due to their slender geometry, tension-only cable systems and a nonlinear response under environmental loadings, tall guyed mast structures exhibit inherently nonlinear behaviour. A complete non-linear dynamic stochastic analysis of truss guyed masts is time-consuming. Therefore, considerable research efforts were invested to simplify the analysis and develop design rules that allow guyed mast to be analysed using equivalent static analysis [6-8]. Although the equivalent static analysis is much simpler than dynamic analysis, modelling and analysis of a guyed mast remain challenging, due to the strong mutual dependence between the adopted mast geometry and the applied load patterns. Therefore, the essential step in the design process is defining an initial layout of the mast that is as efficient as possible, so the need for extensive modifications during the subsequent modelling and analysis steps is minimized [9].

Such challenges prompted researchers to employ automated algorithms that enable systematic exploration of design alternatives, beyond conventional trial-and-error approaches. Since the pioneering work by Bell and Brown [10], numerous studies have addressed the optimization of mast structures, guy configurations and/or pre-stress forces in guys in order to reduce the total mass of the structure [11, 12]. However, for a tall guyed mast, minimizing the self-weight is not necessarily the governing design criterion. Design experience showed that efficiency of the on-site assembly (governed by number of guy attachments through the height, number and dimensions of anchoring blocks, number and weight of assembly parts, etc.) might be even more challenging. Furthermore, the mentioned studies neglected ice loading and nonlinear behaviour of the cables and were generally limited to short masts with only a few guy levels. These limitations significantly restrict the applicability of their findings to real tall masts.

To address the drawbacks, an original MATLAB-based framework [13, 14] was developed to automate the modelling, finite element analysis and steel design utilization checks required in the preliminary structural design of tall anemometric guyed masts. The framework uses SAP2000's Open Application Programming Interface (OAPI) [15], adopts the Eurocode-based provisions and includes relevant load cases, considering both wind and ice actions. In this paper, the application of the framework is illustrated through a representative case study including a tall pinned anemometric guyed mast with a prescribed set of design parameters and extreme loading conditions. The target objectives were evaluated not only in terms of steel consumption, but also to minimize the execution time and simplify the layout. The analysis confirmed the possibility of the developed OAPI to easily reach the target objectives according to contractor's demands, by automatically evaluating hundreds of structural layouts according to the assigned constraints.

2. APPLICATION DEVELOPMENT

2.1. ACTIONS ON THE GUYED MAST STRUCTURE

When analysing the guyed mast, three criteria must be satisfied to ensure that the equivalent static analysis can be performed, according to [16]. Characteristic and design values of the actions, as well as load combinations, should be calculated in accordance with [17-19], taking into account the appropriate reliability class. The following loads should be considered: self-weight, additional dead load (mast equipment), guy prestressing (i.e. 10-20% of the minimum rope breaking force, according to [20-21]), ice load (for the considered glaze ice-class (ICG) [22]) and wind load.

The wind actions on the mast should be determined according to [16, 18]. The total wind effect on the mast structure and guys should be calculated as a sum of equivalent static actions of the mean wind load, and fluctuating component due to wind gusts (patch wind load), for all considered wind directions [16]. The number of patch loads depends on the number of guy levels. The calculation of the wind effect for the iced structure is quite similar to the ice-free case, with the changes in the thickness of the structural elements and appropriate drag coefficients. The effects of ice and wind are combined in two ways: (i) dominant wind (high probability of occurrence) with associated ice (low probability), and (ii) dominant ice (high probability of occurrence) with associated wind (low probability). Note that a coefficient k introduced in [22] reduces the wind pressure on the iced structure for the considered ice class. The seismic action is negligible when compared against the mean wind loading, while the snow and temperature effects are negligible compared to the effects of ice.

2.2. CONSIDERED DESIGN CHECKS

In preliminary design, when an engineering decision should be made upon the mast layout, the ultimate limit state (ULS) and stability checks [19] of the mast legs are performed first, based on the forces obtained from structural analysis. Then, the ULS check [21] of cables is performed, as well. The minimum cable breaking force for guy ropes should be determined based on the selection of the terminations of steel wire ropes. After the structural layout is adopted and the main members are checked, the design of secondary mast members (horizontals, diagonals) is performed, along with the design of joints according to [23] and foundation design [24].

2.3. MODELING AND ANALYSIS

The guyed mast is modelled as an equivalent beam supported by the guys at different altitudes. The central mast is modelled using spatial frame elements, while the cables are modelled using spatial cable elements (with catenary and tension-only behaviour, axial stiffness and no bending nor shear stiffness). The self-weight of the mast legs and cables is assigned automatically, while the additional self-weight originating from the horizontal and diagonal elements of the mast is assigned as an appropriate distributed load. The initial prestressing forces are assigned to the cables, using the target force load case to achieve the target pre-tension. Ice loading is calculated and assigned as an equally distributed gravity load, while mean and patch wind loads are assigned as distributed load patterns in considered directions, for both the iced and ice-free cases. All load combinations are generated as independent nonlinear-static load cases (no superposition), taking into account the structural stiffness from the previous loading cases and P-Δ effects.

In engineering practice, manual modelling usually leads to a time-consuming trial and error process, with repetitive design checks of the adopted layout. Since the wind loads are highly dependent on the mast layout, checking the variant layout possibilities also includes continuous changes in load analysis. Furthermore, manual modelling can also introduce the unintended input errors during the data entry. Due to the highly nonlinear structural behaviour of guyed mast systems, such errors are not easily detected from the analysis results. The above highlights the difficulty of finalizing the guyed mast layout. For masts taller than 100m, engineers must invest heavy effort in the conceptual design phase to examine hundreds of possible layout combinations.

2.4. AUTOMATIZATION PROCESS

The complex structural design process can be automatized using an OAPI developed in MATLAB by the authors [13]. The OAPI enables integration with SAP2000 and efficiently performs the automated analysis process (see Figure 1). In other words, the manual model generation is bypassed without altering the underlying analysis procedure, therefore reducing potential input errors (structural models are generated and analyses are performed in a consistent and systematic manner).

Within the workflow, the script loads the input data regarding the mast geometry, wind speed, ice class, and assigned constraints. All possible combinations of the mast layout data are generated and filtered by applying the geometry constraints. Afterwards, the equivalent static analysis criteria fulfilment is checked and the SAP2000 input files are generated, taking into account the target objectives. Finally, materials, frames and cables are created, corresponding frame and cable sections are assigned, loads within the defined load patterns are applied and nonlinear load cases and load combinations are generated.

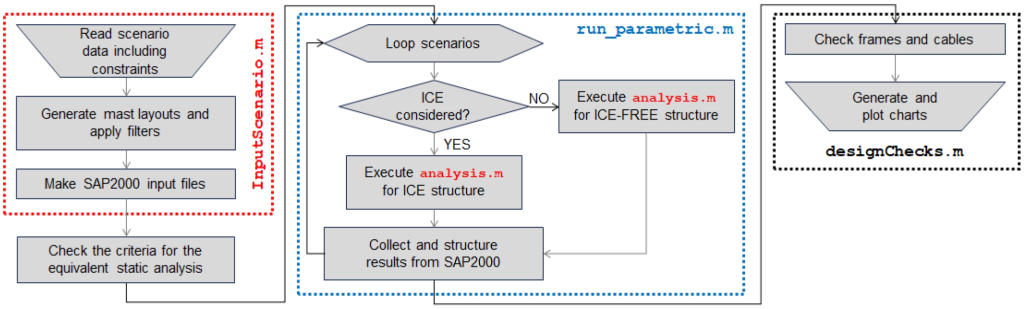

Figure 1: A flowchart of the automated process in finding the best initial mast layout

In the next step, the analysis of all generated structural models, considering both ice and ice-free cases, is carried out, and corresponding results are collected and structured. The results are evaluated through the necessary design checks (ULS in mast legs and cables), and the utilization ratios are calculated and used to evaluate the efficiency of the considered mast layout.

3. CONSIDERED CASE STUDY

3.1. INPUT PARAMETERS

In this paper, a case study considering a 122m mast is presented. Triangular mast layout is adopted as it has lower wind incidence factor and lower wind force coefficients than the square one [16]. Typical mast segment is shown in Figure 2a. Solid circular leg members are selected because their drag (pressure) coefficients are less than twice lower than the flat members. They generate lower wind load on the mast shaft and thus lower compression forces in the legs, but also have lower flexural buckling resistance $N_{b,Rd}$ [19] in comparison against circular hollow sections. The design value of wind load is calculated for three characteristic wind directions (Figure 2b). Reliability class 1 is considered [16].

A location with $v_{b,0}$=29 m/s (max for Serbia) is selected, while two ice classes, ICG-1 and ICG-2, are considered. Although the discrete ancillary items on the structure are almost negligible, their area A_A is adopted as 20% of the structural area A_S. For the sake of simplicity, the weight of equipment is omitted. Steel spiral strand ropes d=12mm, type 1x19 with a nominal tensile strength of 1570 N/mm^2, unit weight w = 830×10^{-7}N/mm^3, fill factor f = 0.76, modulus of elasticity E_Q = 150 GPa (140 GPa for load cases including ice) and breaking force factor K=0.525, according to [21], are used. Three guys per level are selected (Figure 2c).

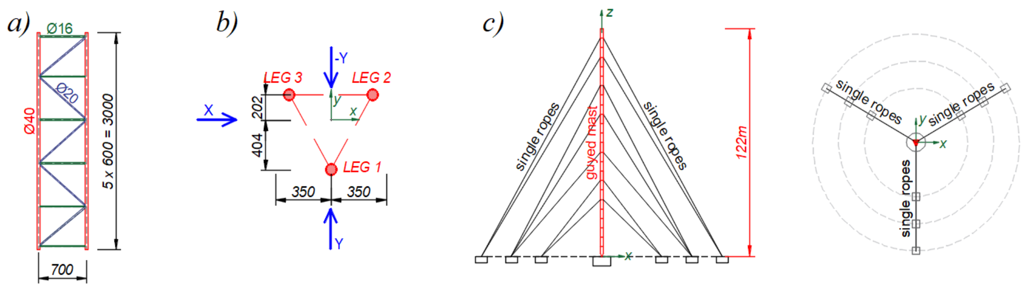

Figure 2: a) Typical mast segment; b) considered wind directions; c) mast layout

The geometry of each guy rope is defined by the attachment level on the mast and the point on the anchoring block. These coordinates are subject to specific geometric and practical requirements and therefore cannot be chosen arbitrarily. By changing the guys' layout, spacing between guy levels, the guy inclination angle and the horizontal distance between anchoring blocks and mast are systematically altered as well, but constrained within rational ranges. The geometry constraints regarding the guy layout are elaborated in Table 1.

Table 1: Guy layout constraints

Property	Value
Spacing between guy levels	9m – 24m
Guy inclination angle	30º - 70º
Max anchoring block-mast distance	60m
Maximum adjacent anchoring blocks spacing	20m

The maximum altitude of the first guy attachment is H_1 = 12m, while the maximum difference of 3m between the shortest and longest guy distance is selected as a constraint. Regarding the anchoring blocks layout, a minimum of 3 guy attachments per block was selected. To provide a relatively even distribution of reaction forces in anchoring blocks, the maximum number of guy attachments per block is limited to be one more than a minimum number in the considered layout.

The primary objective is to compare the efficiency of different mast layouts by varying the following input parameters: guy attachment altitudes and spacing, anchoring block distances and mast steel grades (S235 – S355). Structural parameters such as mast height, mast cross-section, mast segment layout, as well as load parameters (fundamental wind velocity, ice class and the percentage of ancillary equipment) are predefined and held constant.

3.2. RESULTS AND DISCUSSION

Based on the assigned constraints, the application generated a total of 3010 possible mast layouts. The corresponding structural models have been generated and calculated using the OAPI and finally the necessary ULS design checks have been performed and used to evaluate the efficiency of the considered mast layout. Since the steel grade does not influence the analysis results, the design checks have been performed for two different steel grades after the analysis results are collected. The feasible configurations that have passed the ULS design check for both the mast and the cables are collected for both steel grades and the evaluation results are plotted.

Figure 3 illustrates the obtained mast leg ULS utilization ratios U_R, taking into account the necessary number of anchoring blocks, total cable length, max guy level spacing, different steel grades and considered ICG classes. Note that results with U_R > 85% are plotted using bold dots.

Table 2: Number of possible mast layouts, considering different ICG classes and steel grades

	ICG-1		ICG-2	
U_R	S235	S355	S235	S355
< 70%	-	2302	-	-
70 - 85%	820	708	-	9
85 - 100%	2069	-	-	1073
> 100%	121	-	3010 = all	1928

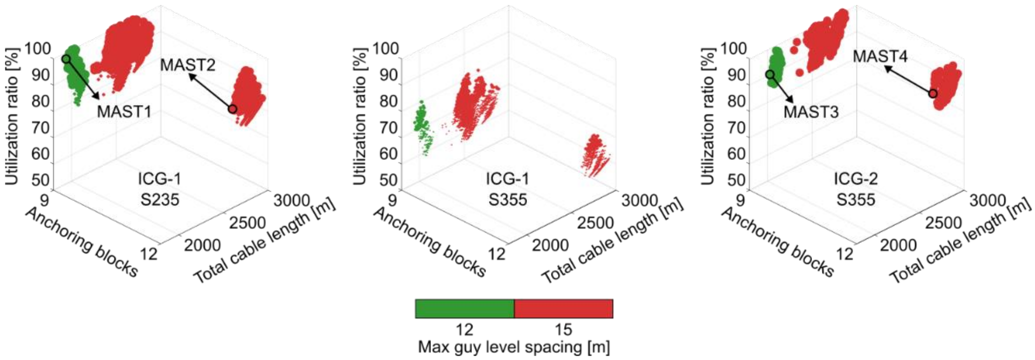

Figure 3: ULS utilization ratios considering different scenarios, by means of: steel grades, ICG classes, number of anchoring blocks, total cable length and maximum guy level spacing

As shown in Figure 3, for the assigned constraints, the feasible structural layout can be achieved by using either 9 or 12 anchoring blocks, with 12 or 15m max spacing between guy levels, resulting in 1948–2932m in total nominal cable length (ICG-1) or 2036-2932m (ICG-2).

For the ICG-1, the use of S355 is not necessary, since 2069 possible mast layouts achieved U_R>85%. In this case, S355 results in relatively lower utilization ratios ($U_{R,max}$ = 81.4%), indicating initially selected layout could be further optimized by reducing the cross sections of both the mast structure and the guys. In contrast, under extreme ice load conditions (ICG-2), S355 must be used, as S235 does not provide any feasible mast layout (see Table 2). Therefore, only S235 layouts for the ICG-1 (Figure 3a) and S355 for the ICG-2 (Figure 3c) will be further discussed.

The ICG-1-S235 layout that minimises the execution time is characterized by 9 anchoring blocks and 15m of max guy spacing (green dots in Figure 3a), with a corresponding minimal total length of the guys of 1948m. This layout is labelled as MAST1 and shown in Figure 4a. The utilization ratio for MAST1 is 97.4%.

A smaller number of anchoring blocks leads to higher reaction forces at each foundation point, which require good soil conditions. If the site is characterized by relatively poor soil properties, a design with a higher number of anchoring blocks (12) may be more appropriate. The most suitable ICG-1-S235 layout comprises 12m of max guy distance and a total guy length of 2613m. It is denoted as MAST2 and shown in Figure 4b. The utilization ratio for MAST2 is 87.4%.

For the ICG-2-S355, two mast layouts are identified as the most suitable: (i) MAST3 (Figure 4c), which minimises the execution time and (ii) MAST4 (Figure 4d) that is more suitable for poor soil conditions. MAST3 is characterized by 9 anchoring blocks, 15m of max guy spacing, minimal total length of the guys of 2036m, with the corresponding U_R = 90.2%. MAST4 has 12 anchoring blocks, 12m of max guy distance, total guy length of 2654m and U_R = 92.6%.

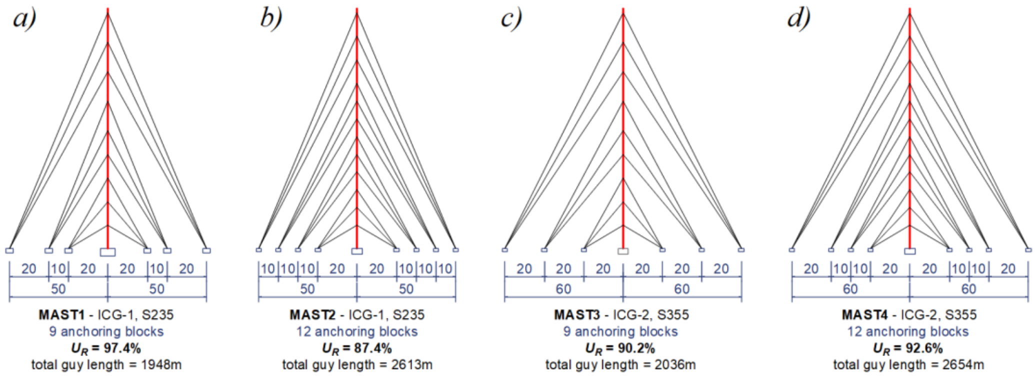

Figure 4: Selected initial mast layouts

4. CONCLUSIONS

The use of equivalent static analysis and a beam-column mast model significantly simplify modelling process of tall steel guyed mast structures. However, the large number of guy ropes, the wide range of load cases and the strong interdependence mast geometry and loading require substantial time and effort in the early stages of structural design. Automation is therefore a logical solution to these challenges. The developed MATLAB-based OAPI framework enables automated modelling, FE analysis in SAP2000 and utilization checks of the anemometric guyed masts. It generates feasible layout combinations and the corresponding FE models, performs the analyses, collects and structures the results, and finally evaluates them through the required design checks.

The efficiency of the developed OAPI framework is demonstrated through a case study involving a 122m guyed mast with extreme wind loading conditions ($v_{b,0}$=29 m/s) and two considered glaze ice classes (ICG-1, ICG-2). The results show that, for ICG-1, S235 steel is sufficient, while under ICG-2 S355 steel is required. For each ice class, two mast layouts are identified as the most suitable: layouts with the minimum number of anchoring blocks (9) and maximum spacing between guy levels (15m) minimize the execution time, while layouts with a higher number of anchoring blocks (12) and maximum spacing between guy levels (12m) are more appropriate for less favourable soil conditions.

The presented study demonstrates the benefits of automating the design process for analytically complex structures such as guyed masts. The developed framework enables fast and efficient evaluation of numerous possible configurations and supports the selection of the final mast layouts that balance material grade, execution efficiency and foundation requirements.

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REFERENCES

[1] Nielsen M. G, Støttrup-Andersen U. Design of guyed masts. 2nd Latin American Symposium on Tension Structures, Caracas, Venezuela, 2005.

[2] Marjanović M, Milojević M, Jočković M. Important aspects in design of anemometric steel masts in the Republic of Serbia. 16th Congress hosted by Association of Structural Engineers of Serbia, Aranđelovac, Serbia, 2022, 492-503.

[3] 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 (2011), 1817-1827.

[4] 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.

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

[6] Madugula M, Wahba Y, Monforton G. Dynamic response of guyed masts, Engineering Structures, 20 (1998), 1097–1101.

[7] Wahba Y, Madugula M, Monforton G. Effect of icing on the free vibration of guyed antenna towers, Atmospheric Research, 46 (1998), 27-35.

[8] Matuszkiewicz M. Calculation of guyed masts in accordance with EN 1993-3-1 standard taking into account mast shaft geometrical imperfections, Engineering Structures, 33 (2011), 2044–2048.

[9] Belavičius R, Jatulis D, Šešok D. Some insights on the optimal schemes of tall guyed mast, Journal of Civil Engineering and Management, 19 (2013) 5, 749-758.

[10] Bell L. C, Brown D. M. Guyed Tower Optimization, Computers & Structures, 6 (1976), 447-450.

[11] Belavičius R, Jatulis D, Šešok D. Optimization of tall guyed masts using genetic algorithm, Engineering Structures, 56 (2013), 239-245.

[12] Belavičius R, Jatulis D, Rusakevičius D. Optimal Schemes of Tall Pinned Masts, KSCE Journal of Civil Engineering, 28 (2024), 904-915.

[13] Jočković M, Milojević M, Martinović D, Fric N, Marjanović M. Towards automating the structural design of guyed masts, Gradjevinar, 2026, article in press.

[14] MathWorks: MATLAB Documentation, The MathWorks Inc, Natick, MA, 2025.

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

[16] 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.

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

[18] 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.

[19] 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.

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

[21] 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.

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

[23] 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.

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