NUMERICAL ANALYSIS AND DETERMINATION OF INITIAL ROTATIONAL STIFFNESS OF BOLTED CONNECTIONS

Klára Buchníčková*,1, Ivan Balázs[1]

*212100@vutbr.cz
[1]Brno University of Technology, Faculty of Civil Engineering, Veveří 331/95, 602 00 Brno

Abstract

This paper deals with the determination of the initial rotational stiffness of some types of bolted connections used in steel structures. The assessment was performed using the finite element method. The connections were classified by their initial rotational stiffness as either rigid, semirigid or pinned according to EN 1993-1-8. The internal forces of a structure can be determined more accurately with the knowledge of connection stiffness which can contribute to the safe and reliable structural design of members.

Keywords

Bolted connection, numerical analysis, steel, stiffness

1 INTRODUCTION

Steel connections are classified as rigid, pinned or semi-rigid. Rigid connections are completely stiff and do not experience any rotation. The full moment is transmitted. Pinned connections, on the other hand, cannot transmit any moment and have a large rotational capacity. Connections that do not fit into these two groups are classified as semi-rigid. They can only partially transmit the moment.

The category of the joints in terms of EN 1993-1-8 [1] is determined by the initial rotational stiffness $S_{j,ini}$ which is defined as the slope of the moment-rotation relation. The moment-rotation curve is generally a non-linear function that describes the behaviour of a connection subjected to a bending moment. It shows the relationship between the applied moment and the rotation of the connection. The rotational stiffness can be expressed as the moment corresponding to the unit rotation of the joint and can be deduced from tests or numerical models using the magnitude of the applied moment and the respective angle of rotation. For the semi-rigid joints, the above-mentioned design standard allows the use of the stiffness S_j (secant stiffness) corresponding to the applied moment $M_{j,Ed}$. Initial stiffness $S_{j,ini}$ can be considered provided the applied moment does not exceed 2/3 of the design moment resistance of the joint $M_{j,Rd}$.

The limits of the joint stiffness categories are described in EN 1993-1-8 in the form of an M-ϕ diagram with boundary lines dividing the area into three zones. If $S_{j,ini}$ is located in zone 1, the connection is rigid, i.e. its stiffness is greater than a defined limit. If it is located in zone 2, the connection is semi-rigid. Otherwise, the connection is classified as nominally pinned.

The connection is rigid if $S_{j,ini} \geq k_b \cdot E \cdot I_b / L_b$. Factor k_b is either 8 for braced systems or 25 for non-braced systems. E stands for Young modulus of elasticity. I_b is the moment of inertia of the connected member and L_b is the length of this member for which the stiffness is determined. The connection is pinned if $S_{j,ini} \leq 0.5 \cdot E \cdot I_b / L_b$.

There was extensive research performed in the field of steel connection stiffness. In [2] authors came to the conclusion that calculations with the actual semi-rigid behaviour of connections may result in more economical structural design than when connections are idealized as completely rigid or pinned. The effect of semi-rigid connections on the bearing capacity of steel tubular members in transmission towers was investigated in [3]. The used method was based on the Gaussian Process Regression model, which showed good accuracy. The reliability of steel tubular members increases when considering semi-rigid connections. In [4] semi-rigid steel end plate connections were analysed. Their rotational stiffness was determined, and the results were compared with experiments. The influence of the plate thickness, bolt type and presence of column stiffeners was analysed. In [5] authors also analysed initial rotational stiffness according to the moment-rotation curve. In addition, they determined the yield point. Some stiffeners can increase the initial rotational stiffness significantly but they can also make the angle connection to enter the yield earlier. A number of studies were performed focusing on the effect of slip due to clearances in the holes for the bolts on the stiffness of the bolted connections. The slip can be characterized as displacement of the joint due to the clearances and it occurs at low levels of load [6]. In [7] results

DOI 10.13164/juniorstav.2024.24048

of experiments of bolted joints with clearances are presented and a multilinear moment-rotation model (taking into account the initial slip of bolts) is proposed.

As the rotational stiffness of the joints in steel structures may considerably influence the distribution of internal forces in the members and therefore affect the structural design, attention should be paid to the proper classification of the joints from the point of view of their stiffness. It indicates the importance of the investigations in this field which could contribute to safe and reliable structural design of the members.

2 METHODOLOGY

The rotational stiffness of three types of bolted connections used in steel structures was determined and compared in this paper. These are beam-to-column connections with either two, four or six bolts. The dimensions and positions of the bolts and their spacings are shown in Fig. 1. Both a column and a beam consist of circular hollow sections (tubes). The profile of the column is CHS 273/10, the beam is of the profile CHS 139.7/6.3. The thickness of the plates is 10 mm. The material of the members is structural steel of S355 grade and the bolts are M16 with 8.8 strength class. The plates are welded to the beam or column, respectively. The end of the beam is closed with a cap made of a circular piece of plate of the identical diameter as the beam.

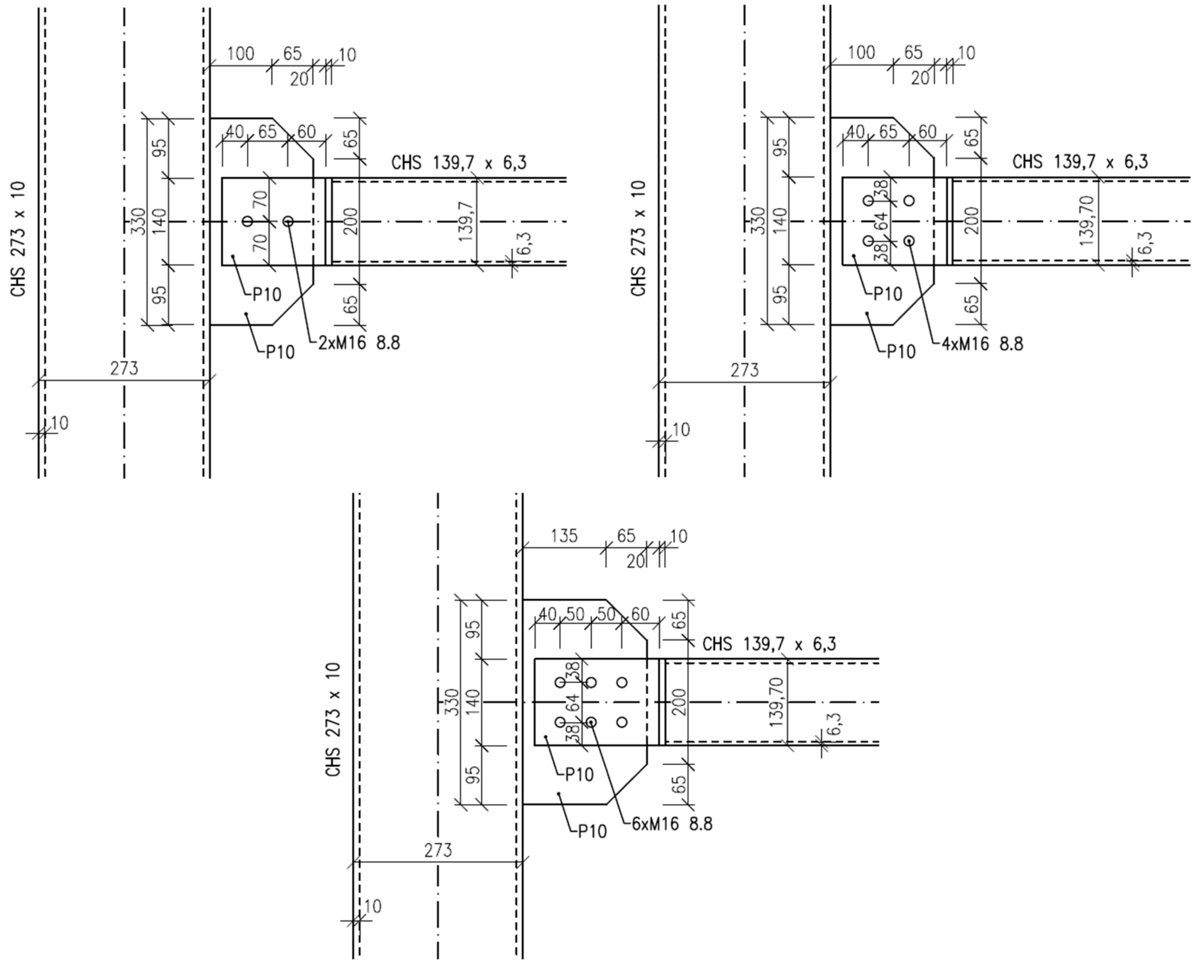

Fig. 1 Scheme of the connections

The analysis was performed using the ANSYS 2023 R2 [8] system based on the finite element method. The material model was bilinear (elastic-plastic) isotropic with small strain hardening. The recommended value of the modulus of elasticity (210 GPa) in terms of [9] was used. The value of the yield strength corresponded to the strength class of the structural steel or the material of the bolts, respectively. Volume (solid) finite elements were used for the numerical analysis. Frictional contacts between the plates on the column and the beam (i.e. between the plates used for the bolted connection of the members) as well as between the bolts and adjacent

DOI 10.13164/juniorstav.2024.24048

surfaces of the plates were considered (the frictional contact areas were considered on heads, shanks and nuts of the bolts). The model can be seen in Fig. 2.

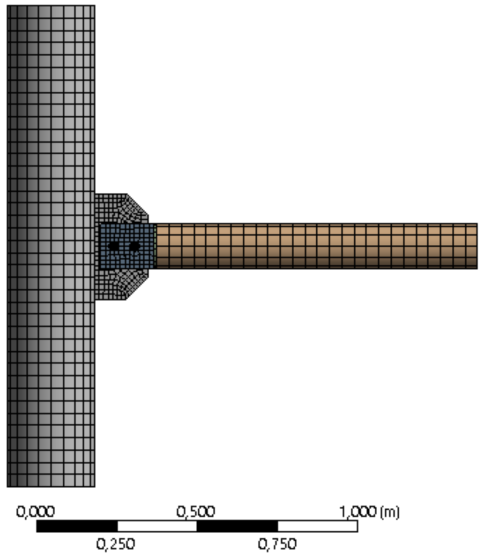

Fig. 2 Meshed model.

The elements used for the model were SOLID186 for the bodies, CONTA174 and TARGE170 for the contacts and PRETS179 for the bolt pretension. The element size of the bodies is shown in Tab. 1. The number of nodes and finite elements in the models is presented in Tab. 2. The welds were simulated as bonded contacts. The diameter of the holes in the plates for the bolts was 18 mm (thus the clearances were considered within the analysis). The length of the column in the model was 1.5 m. The length of the beam was 0.7 m. The column was fixed on both ends.

Tab. 1 Element size.

	Column	**Beam**	**Plates**	**Cap**
size [m]	$4\cdot 10^{-2}$	$4\cdot 10^{-2}$	$1.5\cdot 10^{-2}$	$2\cdot 10^{-2}$

Tab. 2 Number of elements and nodes.

Number of bolts	**Number of nodes**	**Number of elements**
2	13,960	2,223
4	16,425	2,652
6	19,704	3,193

The aim of the analysis was to apply the bending moment on the beam to be resisted by the connection. Its magnitude (and corresponding rotation) is necessary for the determination of the rotational stiffness. The displacement-controlled load was applied at the end of the beam in the form of the defined vertical displacement of 0.2 m. This magnitude of the applied displacement was found to be sufficient to produce a wide-range load-deformation relationship required for the subsequent evaluation.

The geometrically and materially nonlinear numerical analysis (GMNA) was performed in two steps. First, the bolt pretension of a low magnitude (500 N) was applied. Then the displacement of 0.2 m was applied to the end of the beam in 50 substeps. In every substep, deformation was recorded in one control point. The angle of rotation θ of the connection was calculated using this displacement (indicated as u), as shown in Fig. 3.

The moment in the connection M was calculated using the mechanical model in Fig. 4. The calculation was based on the moment equilibrium condition (1). The reactions N_R, V_R and M_R (corresponding to the applied load and required for the calculation) were obtained as the results of the numerical analysis (they were recorded in every substep).

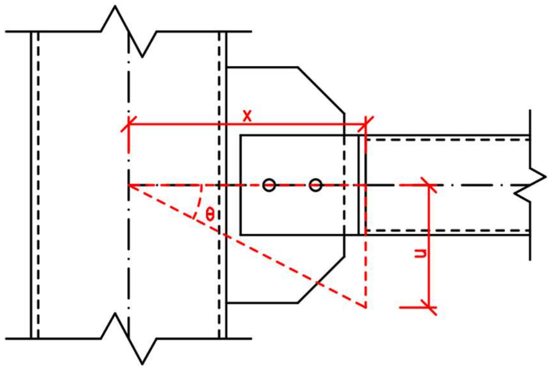

Fig. 3 Determination of the connection rotation.

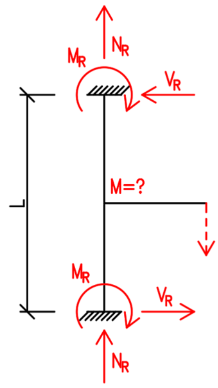

Fig. 4 Mechanical model.

$$M = V_R \cdot L - M_R - M_R \tag{1}$$

where M is the moment in Nm, V_R is the reaction in N, M_R is the moment in Nm, L is the length in m.

With the knowledge of moment M and rotation θ in every substep, the moment-rotation curve can be created. The rotational stiffness was determined using the rotation corresponding to the bending moment equal to 2/3 $M_{j,Rd}$. The design moment resistance of the joint $M_{j,Rd}$ was taken as the minimum from the moment capacities of the bolts, plates and welds. The connection was then classified as rigid, semi-rigid or pinned.

3 RESULTS

The moment-rotation relationships for the investigated cases are presented in Fig. 5. The values of moment and rotation for the calculation of the rotational stiffness are highlighted. The borders between the stiffness categories (rigid, semi-rigid, pinned) are represented by the dashed lines, as seen in Fig. 6, which shows the comparison of the moment-rotation relationships of the three analysed connections. It should be noted that the precise numerical models used for the analysis were created with respect to the actual geometry of the connections including clearances in the holes for the bolts (the diameter of the hole was greater than the diameter of the shank of the bolt). It can be seen from the resulting moment-rotation characteristics that in the initial phase there is only displacement of the bolts in the holes resulting in certain rotation of the connection with almost negligible transmission of the bending moment (only a minimum amount of the moment may be transmitted due to small friction). Once the bolts touch the surfaces of the holes, the connection starts to fully resist the bending moment which is apparent in the moment-rotation characteristic as a sudden change of the slope of the curve. Then the curve flattens due to material nonlinearity. Selected results of the numerical analysis are displayed (deformation and distribution of the equivalent stress; illustrative figures for the connection with four bolts) in Fig. 7.

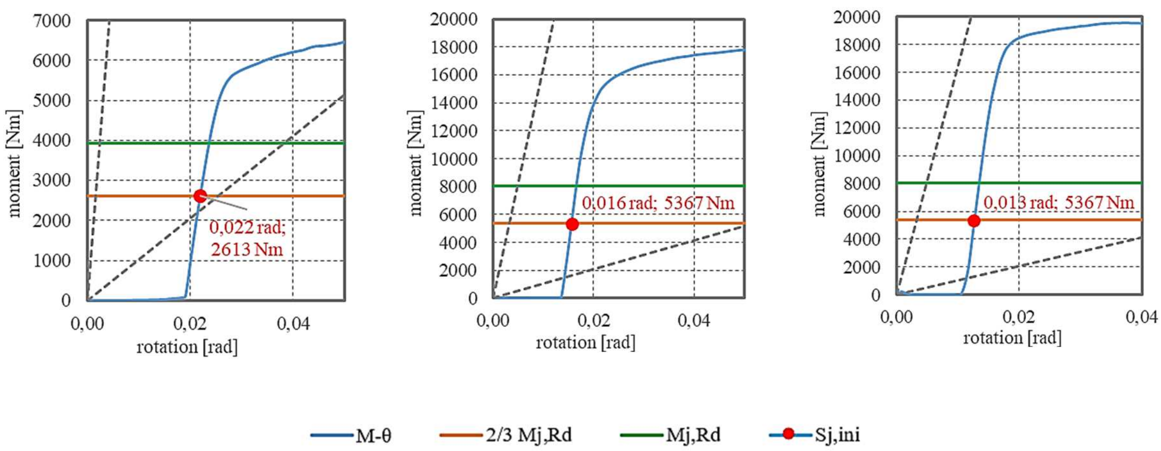

Fig. 5 Moment-rotation characteristics – 2 bolts (left), 4 bolts (middle), 6 bolts (right).

DOI 10.13164/juniorstav.2024.24048

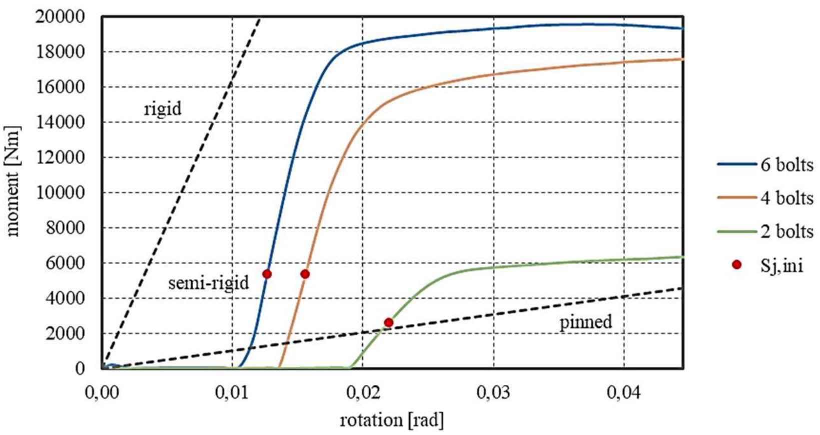

Fig. 6 Moment-rotation characteristics (6 bolts).

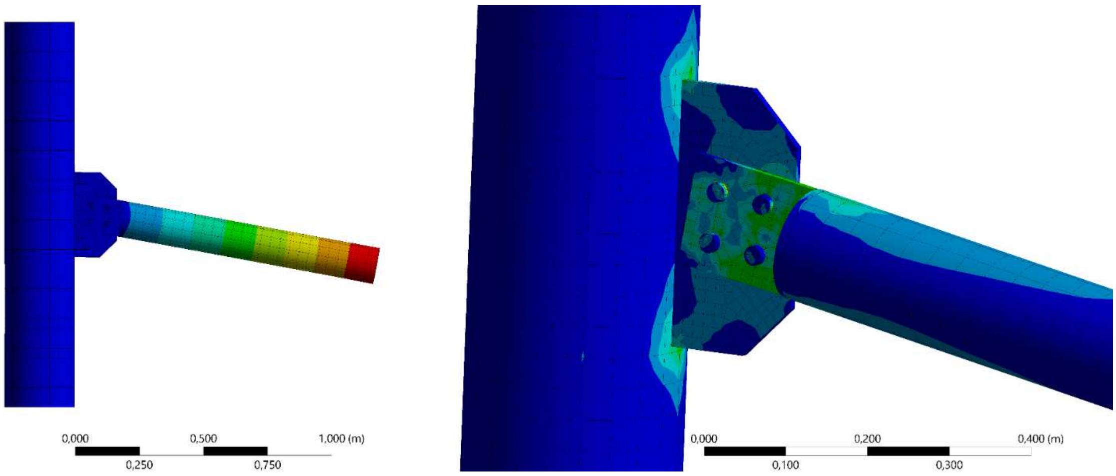

Fig. 7 Deformation and distribution of the equivalent stress.

The stiffness limits are listed in Tab. 3. The calculation was in terms of EN 1993-1-8 [1]. They are calculated according to the equations (2) and (3).

$$S_{j,R} = k_b \cdot \frac{E \cdot I_b}{L_b} \tag{2}$$

$$S_{j,\mathrm{P}} = 0.5 \cdot \frac{E \cdot I_b}{L_b} \tag{3}$$

where $S_{j,R}$ is the limit for rigid connections in MNm/rad, $S_{j,P}$ is the limit for pinned connections in MNm/rad, the factor k_b is 8, E is the Young modulus of elasticity in GPa, I_b is the moment of inertia in m^4, L_b is the length in m.

The length of the member in the formulas for the limit values was considered 6 m (the expected length of the member necessary for the determination of the limits). The results are listed in Tab. 4, $S_{j,ini}$ was compared to the stiffness limits and the joints were classified.

Tab. 3 Stiffness limits.

I_b [m⁴]	L_b [m]	E [GPa]	k_b [-]	$S_{j,R}$ [MNm/rad]	$S_{j,P}$ [MNm/rad]
$5.89 \cdot 10^{-6}$	6	210	8	1.649	0.103

DOI 10.13164/juniorstav.2024.24048

Tab. 4 Stiffness classification.

Number of bolts	$M_{j,Rd}$ [Nm]	2/3 $M_{j,Rd}$ [Nm]	θ at 2/3 $M_{j,Rd}$ [rad]	$S_{j,ini}$ [MNm/rad]	$S_{j,ini} > S_{j,R}$	$S_{j,ini} < S_{j,P}$	joint classification
2	3,920	2,613.3	0.022	**0.119**	no	no	**semi-rigid**
4	8,050	5,366.7	0.016	**0.343**	no	no	**semi-rigid**
6	8,050	5,366.7	0.013	**0.422**	no	no	**semi-rigid**

4 DISCUSSION

The results show that every analysed connection was classified as semi-rigid. The rotational stiffness of the two-bolts connection was 0.119 MNm/rad which is very close to pinned connection ($S_{j,ini}$ = 0.100 MNm/rad). The stiffness of the connection with four bolts was about three times higher than the initial rotational stiffness of the connection with two bolts. The difference in stiffness between the connection with four and six bolts was not that significant. The stiffness of the six-bolt connection was less than four times higher than the stiffness of the two-bolt connection. The values of the rotational stiffness obtained from the numerical investigation can be used within the global analysis of a structure with these types of connections to obtain the actual distribution of internal forces with the effect of the semi-rigid joints. Considering only rigid or pinned connections may not lead to correct results. As the limit values of the stiffness depend on the member length, the classification should be always done for the specific case taking into account the actual lengths of the members.

5 CONCLUSIONS

Specific stiffness values can be conveniently used in the design of steel structures. As the stiffness of the joints may considerably affect the distribution of the internal forces and therefore dimensions of the members, it should be considered as an important parameter for the global analysis of structures. The specific values of the stiffness can be determined using numerical analysis in computational systems based on the finite element method. In this paper, the rotational stiffness of selected bolted connections was determined using precise numerical models. Based on the results, the connections were classified as semi-rigid in terms of the actual design code. The values of the stiffness can be entered into numerical models for analysis of structures with these connections and more accurate magnitudes of internal forces can be obtained. It can be concluded that correct numerical models can demonstrate realistic behaviour of the joints under applied load, including the moment-rotation relation necessary for the determination of the rotational stiffness.

Acknowledgement

The paper was elaborated within the research programme of the Faculty of Civil Engineering, Brno University of Technology No FAST-S-23-8317.

References

[1] EN 1993-1-8: Eurocode 3: Design of steel structures – Part 1-8: Design of joints. CEN, Brussels, 2013.

[2] SIMÕES, L. M. C. Optimization of frames with semi-rigid connections. *Computers & Structures* [online]. 1996, 60 (4), 531–539. ISSN 0045-7949. Available at: https://doi.org/10.1016/0045-7949(95)00427-0

[3] TANG, Z., Li, Z., WANG, T. GPR-based prediction and uncertainty quantification for bearing capacity of steel tubular members considering semi-rigid connections in transmission towers. *Engineering Failure Analysis* [online]. 2022, 142, 1-18. ISSN 1350-6307. Available at: https://doi.org/10.1016/j.engfailanal.2022.106854

[4] BAHAZ, A., AMARA, S., JASPART, J. P., DEMONCEAU, J. F. Analysis of the Behaviour of Semi Rigid Steel End Plate Connections. *MATEC Web of Conferences* [online]. 2018, 149. ISSN 2261-236X. Available at: https://doi.org/10.1051/matecconf/201814902058

[5] QIN, J., WANG, Z., PAN, J., LI, B., FAN, Y. Moment-rotation curve characteristics and initial rotational stiffness calculation method of angle connections. *The Structural Design of Tall and Special Buildings*

[online]. 2022, 31 (3). ISSN 1541-7794. Available at: https://doi.org/10.1002/tal.1906

[6] UNGKURAPINAN, N., CHANDRAKEERTHY, S. R. de S., RAJAPAKSE, R. K. N. D., YUE, S. B. Joint slip in steel electric transmission towers. *Engineering Structures* [online]. 2003, 25 (6), 779–788. ISSN 0141-0296. Available at: https://doi.org/10.1016/S0141-0296(03)00003-8

[7] BALAGOPAL, R., RAMASWAMY, A., PALANI, G. S., PRASAD RAO, N. Simplified bolted connection model for analysis of transmission line towers. *Structures* [online]. 2020, 27, 2114-2125. ISSN 2352-0124. Available at: https://doi.org/10.1016/j.istruc.2020.08.029

[8] ANSYS® Academic Research Release 2023 R2

[9] EN 1993-1-1: Eurocode 3: Design of steel structures – Part 1-1: General rules and rules for buildings. CEN, Brussels, 2011