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METHODOLOGY FOR MODELLING AND STRUCTURAL ANALYSIS OF A COMPLEX LATTICE STRUCTURE

METODOLOGIJA ZA MODELIRANJE I STRUKTURNU ANALIZU KOMPLEKSNE REŠETKASTE KONSTRUKCIJE

Originalni naučni rad / Original scientific paper
Rad primljen / Paper received: 23.08.2025
https://doi.org/10.69644/ivk-2026-03-0339

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Keywords
- modelling
- lattice structure
- structural analysis
- static and dynamic loads

Abstract

The article presents a methodology for complete modelling of a complex spatial lattice supporting structure with all possible static and dynamic loads. The modelling of loads is done due to their specificity and complexity which arises from working regimes of the machine on which the structure is placed, and also from the working conditions that are often unpredictable. By establishing a dependable model of the structure and external loads for a specific real object, the structural analysis is conducted using SAP2000®, the leading engineering software for this purpose. The structural analysis generated output data for the internal loads, deformations, and stresses of all structural components, enabling identification of the most heavily loaded elements and their subsequent assessment. The article also discusses the load function of the structure throughout its lifetime, an essential characteristic for the operation and maintenance methods derived from a dedicated methodology.

Ključne reči
- modeliranje
- rešetkasta konstrukcija
- strukturna analiza
- statička i dinamička opterećenja

Izvod

U ovom radu je predstavljena metodologiju za potpuno modeliranje složene prostorne rešetkaste noseće konstrukcije i svih mogućih statičkih i dinamičkih opterećenja. Modeliranje opterećenja je izvršeno s obzirom na specifičnost i složenost, koje proizlaze iz režima rada mašine na kojoj se ova konstrukcija nalazi, a i iz uslova rada koji su često nepredvidljivi. Uspostavljanjem pouzdanog modela konstrukcije i spoljašnjih opterećenja za dati realni objekat, sprovedena je strukturna analiza korišćenjem SAP2000®, vodećeg inženjerskog softvera za ovu svrhu. Strukturnom analizom se generišu izlazni podaci za unutrašnja opterećenja, deformacije i naprezanja svih komponenata konstrukcije, čime se omogućava identifikacija najteže opterećenih elemenata i njihova naknadna procena. U radu se takođe razmatra funkcija opterećenja konstrukcije tokom njenog životnog veka, što je suštinska karakteristika za metode rada i održavanja, izvedenih iz namenske metodologije.

INTRODUCTION

The author is a scientist who has been researching supporting steel structures for three decades. Most of her published papers and articles are within that research area.

The investigation mainly covers lattice-carrying structures of rotating excavators in the Suvodol-Bitola open-pit coal mine in the R. N. Macedonia.

The author connects the practical experiences from measurements and experiments with the study of theoretical knowledge from the world literature in this field, which is a challenge for her as a professor of the subject of *Metal (steel) structures* at the Faculty of Technical Sciences, from which come the bibliographic units /1, 2/, as the basis for this and many other articles.

The first challenge in solving practical problems with a scientific approach in excavator supporting structures during excavator exploitation is the research for the doctoral dissertation /3/.

In the subsequent period, other challenges emerged, along with many scientific papers. This article aims to deepen the research that started and was published in the papers and articles presented below over an extended period.

The paper analyses the mathematical modelling of the clamps and supporting structures of the rotating excavator working wheel /4/. The paper presents a model for calculating wind loads on the supporting structure of a rotating excavator for different wind directions /5/. The modelling of a supporting structure for testing under static loads is carried out in /6/. Paper /7/ presents the modelling of a supporting structure for testing under dynamic loads.

Modelling wind loads with a direction of lateral resistance of digging for the supporting structure of a rotating excavator working wheel and examining the structure's deformation state for the structure's horizontal position is found in /8/. A model of wind loads in the direction opposite to the lateral resistance of digging for the supporting structure of a rotating excavator working wheel is presented in /9/. The deformation state of the structure is examined for the horizontal position. Paper /10/ defines a methodology for setting up load diagrams for the clamps of an excavator's supporting structure. Theoretical calculations and experimental tests using strain gauges to determine the static load on the clamps of a supporting structure and to demonstrate how the position of the supporting structure influ-

ences the magnitude of that load is examined in /11/. Guidelines for modelling lattice girder structures with a cantilever design are provided in /12/, which lays the foundation for this work. In /13/, a methodology is established, and the load functions for clamps and elements of a characteristic joint in the working wheel supporting structure of a rotating excavator are determined, which serves as a reference for the structure discussed here.

Although lattice girders are utilised in various engineering fields, such as mechanical engineering and machinery mechanisation, they have received limited scientific scrutiny, particularly in excavator structures, including static and dynamic analyses.

There is no universal approach or methodology for the structural analysis of lattice structures; therefore, every contribution in this area is essential to the field. Given this context, the author aims to establish a methodology for modelling and structurally analysing a complex lattice structure through a specific example, focusing on the supporting structure of the SRs-630 rotating excavator.

The author also establishes the load function of the structure based on a methodology specifically designed for this purpose.

LITERATURE REVIEW

In addition to the references mentioned above, the activities carried out in this article utilise scientific knowledge from books /14, 15/ on steel structures and their constituent elements.

In addition to being based on one's own experience, the strength assessment of structural elements is also conducted in consultation with the guidelines presented in /16/. The SAP2000® software package and book /17/ are beneficial in computer modelling of the structure. A challenge faced here is applying the advanced methods for structural analysis outlined in /18/.

Experiences on structural analysis presented in /19/ were also of great help, especially those on excavators presented in /20/. According to /21-25/, the structural analyses of large structures, such as excavators, involve evaluating the constituent elements based on material tensile strength and the maximal stress at specific locations.

The dynamic model for the supporting lattice structure of a rotating excavator, presented in /26/, is compared and studied with the model in this article to draw conclusions related to model validation.

In /27/, a modal and static analysis of lattice structure and is conducted and assessed according to the lowest specific deformation, providing valuable insights. The method for calculating the critical load of an axially compressed truss of the lattice structure presented in /28/ is beneficial to the analysis of the compressed trusses of the structure discussed here. When spatially modelling the lattice in this article, the experience presented in /29/ to analyse the three-dimensional girder models were also considered.

REAL MODEL OF THE STRUCTURE

The structure is a spatial steel lattice of length 18.55 m and a rectangular cross-section 3.5 m wide and 2.4 m high. It is made of a combination of materials, the basic one being steel Č 0371 (according to the national MKS standard).

Due to the complex structural design, its real model (Fig. 1) is established first. This model is close enough to the actual structure so that the mathematical model required for structural analyses is further established on its basis.

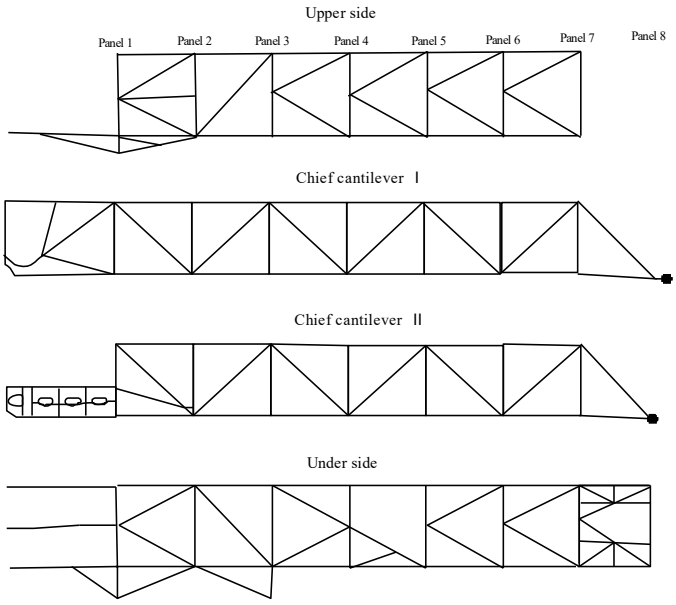


Figure 1. Real model of the structure.

The structure (according to Fig. 1) consists of two main girders (chief cantilever I - front side, and chief cantilever II - back side of the lattice), one upper and one under connection (upper and underside of lattice), and two transverse frames (transverse frame 1 - in panel 1 and transverse frame 7 - in panel 7).

From the transverse frame 1 to the left, the structure is designed as a cantilever girder of length 4.56 m.

On one side (far right in Fig. 1), the structure is movably supported on two hinge joints, and on the other side (in panel 1 of the upper connection), it is hung on two clamps.

This structure can move in a horizontal and vertical plane. In a horizontal plane, movement is enabled by rotating the lower structure of the excavator. In a vertical plane, movement is from the lowest position, where digging is done 1.5 m below the stratum, to the highest position, where digging is done 17 m above the stratum.

MATHEMATICAL MODEL OF THE STRUCTURE

The mathematical model of the structure with its component elements is shown in Fig. 2.

Figure 3 shows the structure's joints, location, and the adopted numerical designation. The structure has 47 joints. The support points are hinge connections (joints 15, 30, 46, and 47).

The structure has 111 trusses, and Fig. 4 shows their location and numerical designation. A large number of the elements (trusses) of the structure are of complex shape, the cross-section of which is composed of two L-profiles, and their appearance is shown in Fig. 5. The remaining trusses of the structure have a cross-section in the form of a T-profile, an I-profile, with a rectangular cross-section (□) and

profiled supports in the form of a cross (+). The joints of the profiles are made with filler plates and rivets. Clamps have a complete rectangular cross-section. The 47 sizes of cross-sections have been systematised in this structure.

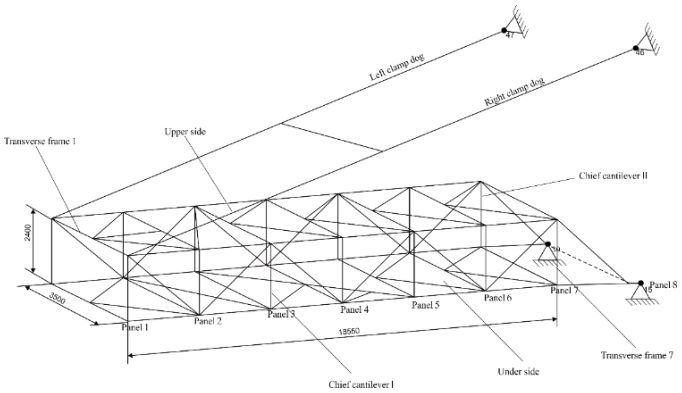


Figure 2. Mathematical model of the structure.

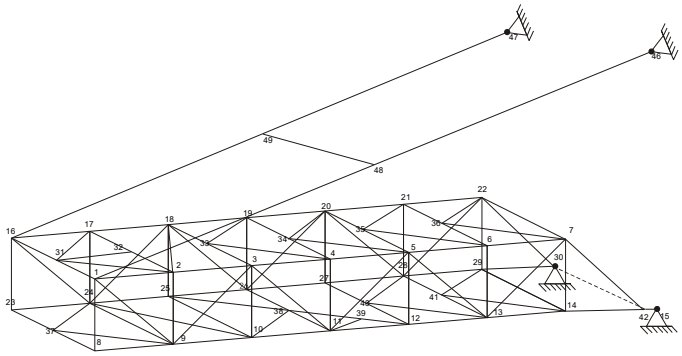


Figure 3. Joints of the structure.

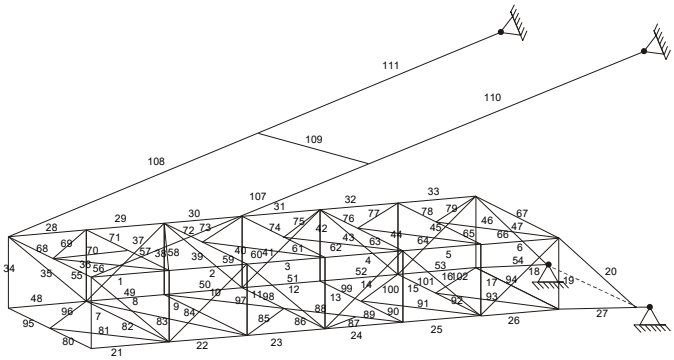


Figure 4. Trusses of the structure.

STATIC LOAD MODELLING

The static load on the structure is the self-weight of all elements that make up the structure, which is 110355 kg or 1082582.6 N, while only the metal structure weighs 34720 kg or 340603.2 N.

Given that this is a complex structure, the number of elements is large, which makes it difficult to enter the loads into the mathematical model during computer calculation. Following a methodology developed for this purpose, the static load of structural elements of the transverse frame 1 on the left (Fig. 1) that exists in the real model is replaced in the mathematical model with an equivalent joint's load, shown in Fig. 6.

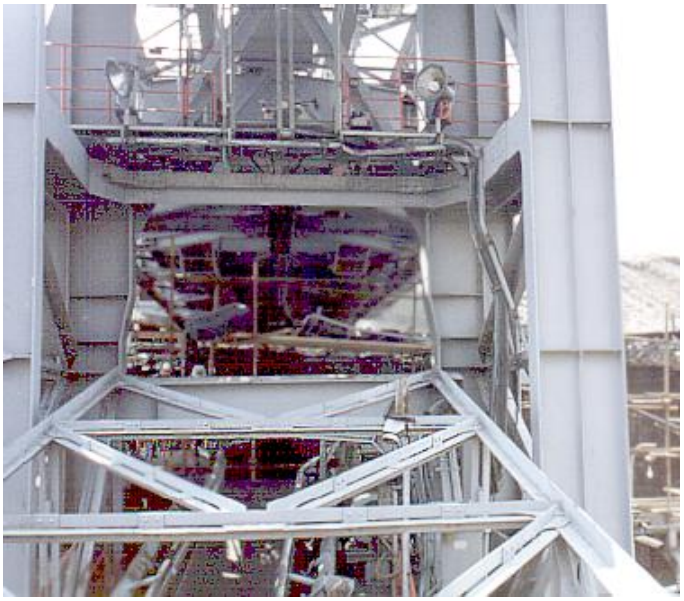


Figure 5. View of part of the structure.

The static load on the structure is analysed for its three characteristic positions: horizontal position; uppermost position; and undermost position.

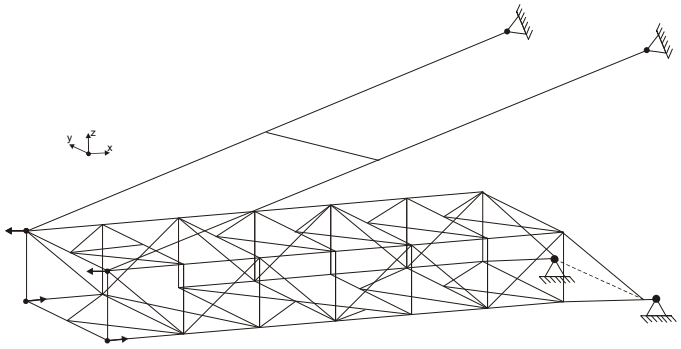


Figure 6. Equivalent joints' load from static load.

DYNAMIC LOAD MODELLING

Without wind action

The dynamic load on the structure is determined by its following characteristic positions and working regimes:

- horizontal position and turning to the left;
- horizontal position and turning to the right;
- uppermost position and turning to the left;
- uppermost position and turning to the right;
- undermost position and turning to the left;
- undermost position and turning to the right.

Figure 7 shows equivalent joints' load from the weight of the elements to the left of the transverse frame 1 and from the digging resistances for turning to the left, and Fig. 8 for turning to the right.

The dynamic load includes the loads from the digging resistances for defined working conditions of the excavator, which are transferred to the structure and components from the static load. The distribution of the loads on the structure from digging resistances is carried out according to a methodology developed for this purpose, i.e., they were replaced by equivalent joints' loads in the transverse frame 1.

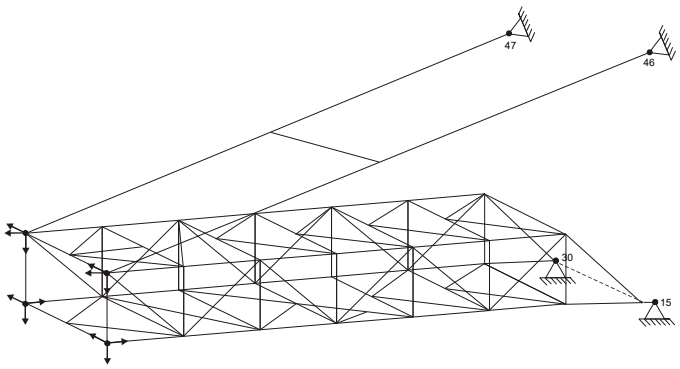


Figure 7. Equivalent joints' load from dynamic load without wind when turning to the left.

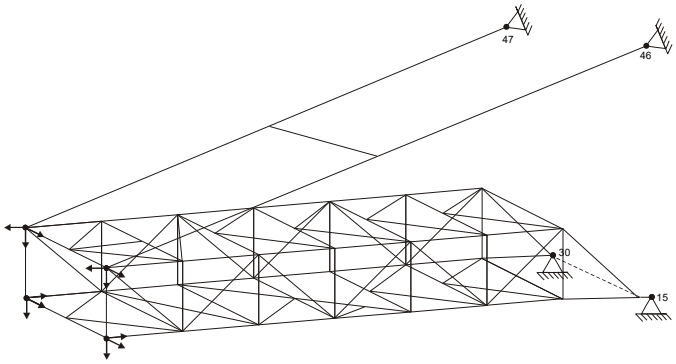


Figure 8. Equivalent joints' load from dynamic load without wind when turning to the right.

With wind action

Wind is a dynamic load on a structure, and its influence is a rather complex problem. The influence of wind is reduced to static and dynamic action on the structure. The forces of wind loading take into account, in addition to the static component of the wind for a given climatic region, the size of the surface on which they act, as well as the shape of the elements on which the wind acts.

Wind with lateral resistance direction

The dynamic load on the structure under the action of wind with the mentioned direction is determined for all the above-defined characteristic positions of the structure.

Figure 9 shows the equivalent joint load on the structure from the action of wind with lateral resistance direction (resistance from excavator digging) for turning to the left, and Fig. 10 shows the load for turning to the right.

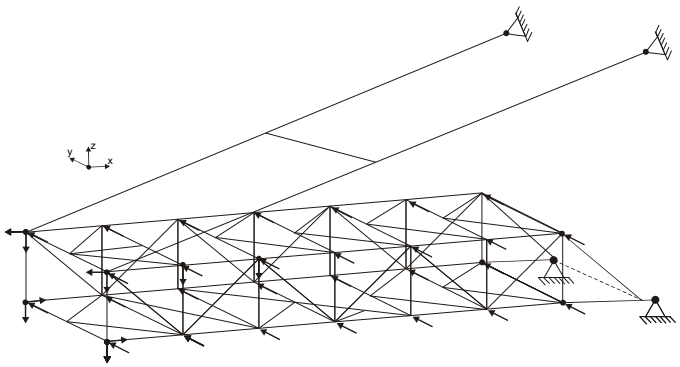


Figure 9. Equivalent joints' load from dynamic load and wind with lateral resistance direction when turning to the left.

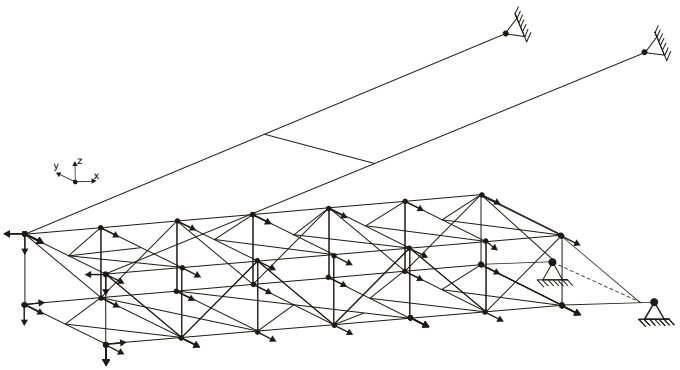


Figure 10. Equivalent joints' load from dynamic load and wind with lateral resistance direction when turning to the right.

In the joints of transverse frame 1, in addition to the wind load, the load from the weight of elements to the left of it and from the digging resistances are taken into account.

Wind with opposite resistance direction

The dynamic load on the structure under the action of wind with the opposite resistance direction is determined for all structure positions and when exposed to wind with the lateral resistance direction.

Figure 11 shows the equivalent joint load on the structure from the action of wind with opposite resistance directions for turning to the left, and Fig. 12 shows load for turning to the right.

In the joints of the transverse frame 1, in addition to the wind load, the load from the weight of the elements to the left of it and from digging resistances are taken into account.

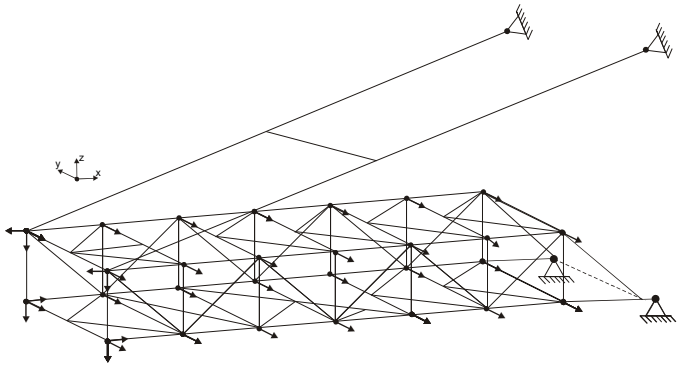


Figure 11. Equivalent joints' load from dynamic load and wind with opposite resistance direction when turning to the left.

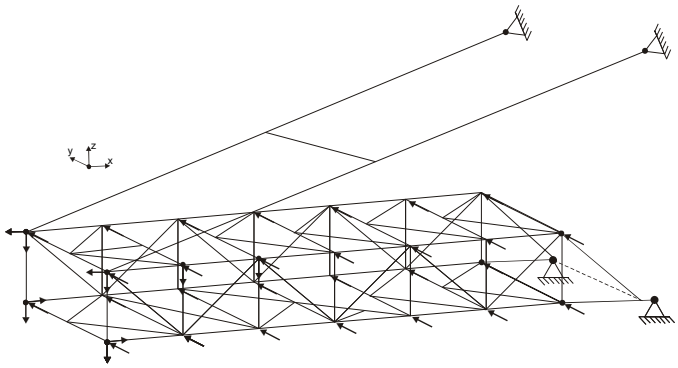


Figure 12. Equivalent joints' load from dynamic load and wind with opposite resistance direction when turning to the right.

DEFORMATION STATE OF THE STRUCTURE

From static load

The deformation state of the structure is obtained with SAP2000 software for the above-defined characteristic positions. Figure 13 shows the deformation state for the horizontal position of the supporting structure. In this position, the displacements of structure elements are the largest compared to the other two positions (upper- and undermost).

Figure 13, with numerical values, gives minimum and maximum displacements of joints in the structure in cm along the three axes of the global coordinate system set at joint 8 (shown in Fig. 3), with the orientation of axes as indicated in Fig. 13.

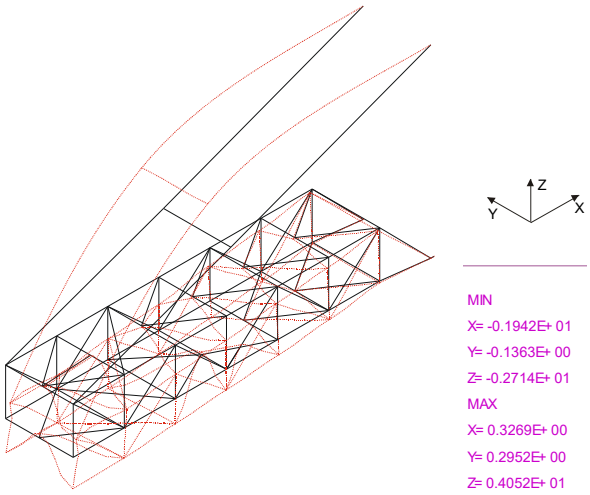


Figure 13. Deformation state of the structure from the static load for the horizontal position.

From dynamic load

For all the above-defined cases of dynamic loading at minimum and maximum excavation resistances, without- and with wind action, the deformation state of the structure from dynamic loading is determined identically as the deformation state from static loading.

Figures 14, 15, and 16 show the structure's deformation state for the three most unfavourable loading cases.

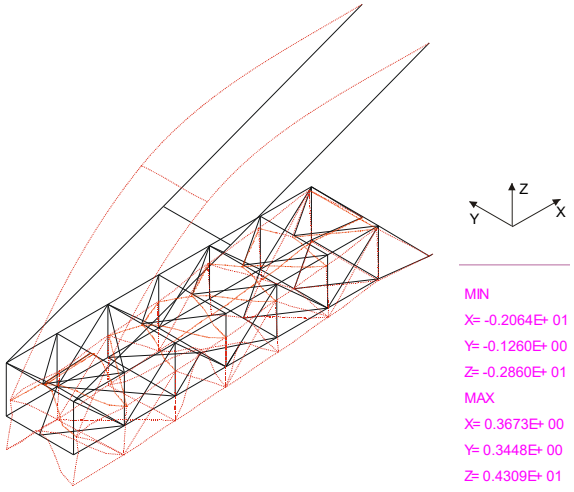


Figure 14. Deformation state of the structure from dynamic load, for horizontal position and turning to the left, at maximum resistance, without wind action.

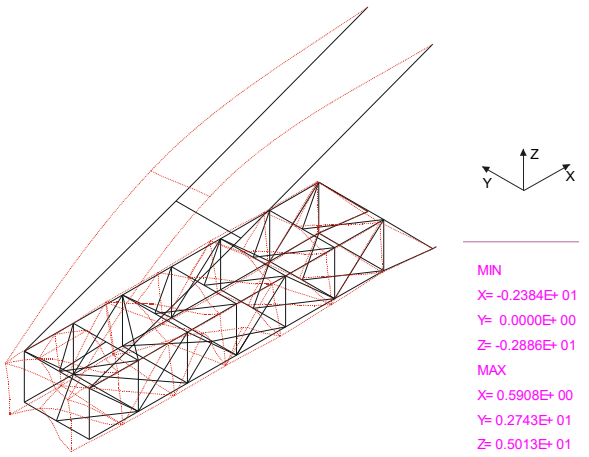


Figure 15. Deformation state of the structure from dynamic load, for horizontal position and turning to the left, at maximum resistance, and wind with lateral resistance direction.

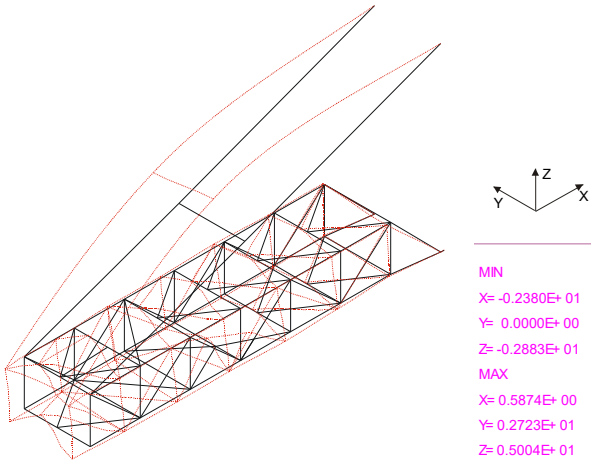


Figure 16. Deformation state of the structure from dynamic load, for horizontal position and turning to the right, at maximum resistances, and wind with opposite resistance direction.

STRESS STATE OF THE STRUCTURE

By thorough analysis of the output data obtained from the static calculation of the structure with SAP2000 software, for all the above-defined load cases, the most unfavourable load cases are determined:

- horizontal position of the structure and turning to the left, at maximum resistance of digging, without wind action;
- horizontal position of the structure and turning to the left, at maximum resistance of digging, and wind with lateral resistance direction;
- the horizontal position of the structure and turning to the right, at maximum resistance of digging, and wind with opposite resistance direction.

Checking the static strength of the structure

The static strength check of the structural elements is carried out for the most loaded truss members (trusses 41, 45, 77, and 79, according to Fig. 4) in the most unfavourable wind-loading cases mentioned above. Results of this activity are systematically presented in Tables 1 and 2.

From a comparison of calculated tension and pressure stresses with permissible stresses for each of the listed trusses, the following conclusions follow:

- the most loaded truss of the structure, in the most unfavourable loading cases, met the condition for static strength (calculated stresses should be lower than permissible ones);
- as previously stated, all structure trusses meet static strength conditions in each working regime and operating condition.

Table 1. Horizontal position of structure and turning to the left, at max. resistance of digging and wind with lateral resistance direction.

	Tension stress		Pressure stress	
Truss	Calculated [kN/cm^2]	Permissible [kN/cm2]	Calculated [kN/cm^2]	Permissible [kN/cm^2]
41	13.68	22.6		
45	14.91	22.6		
77			10.08	14.1
79			12.28	14.1

Table 2. Horizontal position of structure and turning to the right, at max. resistance of digging, and wind with opposite resistance direction.

	Tension stress		Pressure stress	
Truss	Calculated [kN/cm^2]	Permissible [kN/cm^2]	Calculated [kN/cm^2]	Permissible [kN/cm^2]
41	13.65	17.3		
45	14.88	21.8		
77			10.04	21.7
79			12.25	20.09

LOAD FUNCTION OF THE STRUCTURE

The working life of the structure's components determines its total exploitation life. It is reasonable to expect that the most stressed elements of the structure will have the shortest working life.

Based on the previous analysis, the most loaded joint in the structure is the joint marked 24 in Fig. 3. The assessment of which joint is the most loaded is based on the analysis of research results for external loads distribution in the structural elements and the causes of deformations and stresses in them.

The load function of joint 24, i.e., of its constituent elements, will be a load function of the structure. Since each of the constituent elements of joint 24 (that is, the trusses 35, 36, 37, 48, 49, 82, 83, and 96, shown in Fig. 17) during the exploitation life of the structure receive different forces in magnitude and direction (tension or pressure) and the load functions for each of them are different.

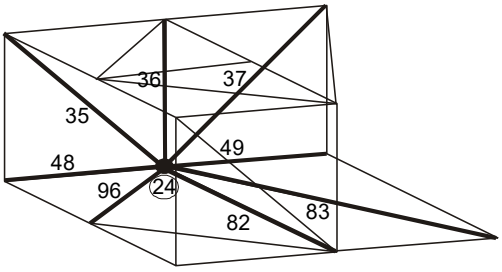


Figure 17. Disposition of trusses of the joint 24.

The analysis of the load functions for component trusses of joint 24 shows that truss 49 is the most loaded. Its load function is shown in Fig. 18, which also represents the load function of joint 24, i.e., the load function of the structure, as stated.

The structure's load function is essential for assessing its total exploitation life without damaging its constituent components.

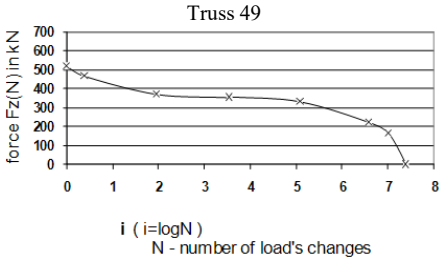


Figure 18. Load function of the joint 24.

CHARACTERISTIC MAGNITUDES FOR THE STRUCTURE

The characteristic magnitudes for the structure are the output parameters from the structural analysis for joint 24, the most loaded joint in the structure, in the most unfavourable position of the structure (without wind action and with wind action in both mentioned directions), and they are presented in Tables 3-8.

Table 3. Forces and stresses in trusses of joint 24, without wind.

	Horizontal position, turning to the left at max. resistance		Horizontal position, turning to the right at max. resistance	
Truss	Axial force [N]	Stress [N/cm^2]	Axial force [N]	Stress [N/cm^2]
35	-5.69	-0.23	-5.12	-0.21
36	-12.16	-0.65	-12.16	-0.65
37	77.18	4.11	76.61	4.08
48	-310.31	-4.06	-308.67	-4.04
49	-372.33	-6.10	-368.66	-6.04
82	-0.2	0.00	0.2	0.00
83	0.49	0.00	-0.49	0.00
96	-0.35	0.00	0.35	0.00

Table 4. Displacements at joint 24, without wind.

	Horizontal position, turning to the left at max. resistance			Horizontal position, turning to the right at max. resistance		
Joint	Displacement [cm]			Displacement [cm]		
24	x-axis	y-axis	z-axis	x-axis	y-axis	z-axis
	0.316	0.23	-2.76	0.313	0.285	-2.76

Table 5. Reactions at joint 24, without wind.

	Horizontal position, turning to the left at max. resistance			Horizontal position, turning to the right at max. resistance		
Joint	Reactions [kN]			Reactions [kN]		
24	*x*-axis	*y*-axis	*z*-axis	*x*-axis	*y*-axis	*z*-axis
	0	0	-35.8	0	0	-35.8

Table 6. Forces and stresses in trusses of joint 24 with wind.

	Wind with lateral resistance direction		Wind with opposite resistance direction	
	Horizontal position, turning to the left at max. resistance		Horizontal position, turning to the right at max. resistance	
Truss	Axial force [N]	Stress [N/cm^2]	Axial force [N]	Stress [N/cm^2]
35	-59.5	-0.242	-58.93	-2.40
36	-12.16	-0.65	-12.16	-0.65
37	130.99	6.97	130.42	6.94
48	-313.79	-4.11	-312.15	-4.09
49	-522.33	-8.56	-518.66	-8.50

82	-32.61	-0.29	-32.33	-0.29
83	81.53	0.74	80.55	0.73
96	-21.66	-0.29	-20.96	-0.28

Table 7. Displacements at joint 24, with wind.

	Wind with lateral resistance direction			Wind with opposite resistance direction		
	Horizontal position, turning to the left at max. resistance			Horizontal position, turning to the right at max. resistance		
Joint	Displacement [cm]			Displacement [cm]		
24	*x*-axis	*y*-axis	*z*-axis	*x*-axis	*y*-axis	*z*-axis
	0.316	0.23	-2.76	0.313	0.285	-2.76

Table 8. Reactions at joint 24, with wind.

	Wind with lateral resistance direction			Wind with opposite resistance direction		
	Horizontal position, turning to the left at max. resistance			Horizontal position, turning to the right at max. resistance		
Joint	Reactions [kN]			Reactions [kN]		
24	*x*-axis	*y*-axis	*z*-axis	*x*-axis	*y*-axis	*z*-axis
	0	20.53	-35.8	0	20.53	-35.8

CONCLUSION

Contemporary methodology is used to study the global deformity-stress condition of the structure, and an original model for structural analysis of supporting structures is set up.

This model is significant because it can be generalised to test other structures with similar structural performance.

The research shows that static load is maximum in the horizontal position of the structure and minimum in the uppermost position.

The loads for the undermost position are smaller than those for the horizontal position and larger for the uppermost position of the structure.

The research shows that the most significant dynamic load is for the horizontal position of the structure and turning to the left, that is, to the right.

Then, according to size, follow the undermost and uppermost positions. The wind's action increases the load.

The model shows the changes in forces in all the structure's constituent elements for static and dynamic loads.

The model for testing the global deformity-stress state of the structure from static and dynamic loads for all theoretical loading cases clearly shows the type of deformations and the magnitudes of maximum and minimum displacements of structural joints. This model also determines the magnitudes of global stresses in all elements of the supporting structure for the theoretical loading cases.

The research results on the global deformity-stress state of the structure are analysed to define the most unfavourable loading regimes: horizontal position and turning to the left, at maximum digging resistance, and wind with lateral resistance direction; and horizontal position and turning to the right, at maximum digging resistance, and wind with the opposite resistance direction.

The general conclusion from the testing of static strength of the most loaded elements of the structure is that the static strength of the structure is satisfactory because even in the most unfavourable cases of loading, the calculated stresses are lower than the permissible ones by at least 13 %.

With the original methodology for obtaining the time load function of the structure, objective parameters for evaluating the total working life are obtained without damaging the structural components.

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