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Stress-strain conditions of steel rod structures nodes

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Abstract. To obtain qualitative and quantitative indicators of changes in the stress-strain state of the nodes of steel bar structures, we identified four characteristic types of nodes. On the basis of modeling in the "Lira-CAD" software package, we analyzed the stress-strain state of four types of nodes for steel trusses with a symmetric and asymmetric design solution. For the research, a calculation of volumetric models of nodes according to the fourth strength theory was performed. At the current moment, the choice of the required thickness of the truss gusset is performed according to the value of the maximum force in the rods. During the nodes modeling it was found that the safety factors depending on the node type for the symmetrical design solution are more than 40 %. The obtained data allow us to reduce the thickness of the gusset taking into account design constraints. It was found that the safety factors depending on the node type for the asymmetric design solution are 7–90 %. The simulation results substantiated the possibility of reducing the gusset thickness for node type 3, and for node types 1, 2 and 4, they showed the necessity of increasing the thickness taking into account design constraints. We derived the refined dependences between the gusset thickness and the maximum force in the attached rods for each structural type of nodes. Based on results of the analysis, we developed recommendations for calculating the most typical types of nodes and presented them in the form of tables and dependencies. For a constructive solution of fastening of gusset braces at an acute angle, we analyzed the influence of the eccentricity value on the stress in gussets. We determined that the main parameter influencing to the stress-strain state of the gusset is the displacement of attached element relative to the axis of the elements fastening. We derived dependences and made graphs of the displacement influence on stresses for different values of gusset thickness.

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1. Introduction

1.1. Definition of the research object

More than 60 % of all building structures can be safely attributed to rod systems. More than 30 % of them are hinge-rod systems: roof trusses structures, braces elements.

In modern normative, guidance and reference literature fully describes the work of rods under load and formalizes it in the form of calculation methods. Most rod fastenings in hinge-rod systems are made using fastening plates (gussets). Currently, there are tables for choosing the gussets thickness, but the methodology for plates design is not formalized.

It is noteworthy that the regulatory documents allow the calculation of rods of lattice structures with rod length to cross-sectional ratio of more than 10:1, however, the gusset is undergoing the complex stress-strain state (SSS).

Complex SSS is caused not only by the fact that the force from the rods acts on the plate in different directions, causing both tension zones and zones of constrained compression (shear), but also due to the arising local moments. Local moments arise in the area of fastening of the plate's rods in case of fastening with two or more bolts or fastening by welding.

The research subject is the phenomenon of changing the stress-strain state of the plates under study when changing the variable parameters.

1.2. Analytical literature review, which examines the current situation in the modern scientific community on this problem

The field of the plates operation was researched by V. Biderman [1], H. Osama [2], S. Timoshenko [3], N. Streletskiy [4], V. Ignat'ev [5].

I. Bubnov proposed the method for integrating differential equations for solving boundary value problems [1].

B. Galerkin proposed the similar method for integrating differential equations, which is widely used for calculating rectangular plates for various models of loading and plate fastening [2].

S. Timoshenko aspired to solve the problems of stability of homogeneous and isotropic thin rectangular plates under the assumption that the deflections of the plates are small in comparison with their thickness, which ensures the non-deformability of the middle surface. Such problems are described by the linear homogeneous equation in partial differentials [3].

Chapter 12 of Timoshenko's book [3] considered the principles of calculating a plate under the combined action of transverse loads and forces in its midplane, uniform tension. N. Streletskiy investigated the experimental installation of gussets in the nodes of heavy trusses [4]. The works of V. Ignat'ev showed that the most effective method for solving problems of rod systems calculating is the method of discrete finite elements (MDFE). The method makes it possible to consider the features of structural geometry, fastening conditions and the load form with the most possible accuracy [5].

In the regulatory and guideline literature there are no researches that form the basis for the table of recommended thicknesses [6] and [7], as well as the method for calculating plates for the action of longitudinal multidirectional forces.

A review of the shaping of steel rod systems is performed in a number of modern researches [12, 13].

Operation under load of plates in rod structures is considered in researches [14, 15].

The plane stress-strain state of steel is described in the relevant chapters of the normative documents [11].

Currently, active numerical and experimental researches of operation under load are being carried out for steel plates working as stiffening diaphragms in the frames of multistory buildings. The results are described in the works of M. Ramezani [17, 18], I. Verma [19], Y. Ly [20], Z. Zhou [21], O. Haddad [22] and also in the works [23–25].

The truss' gussets plates act like diaphragm plates of multistory buildings in a complex stress-strain state, however, the truss gusset plate is fixed on only one side, and the stiffening diaphragm plates are fixed on four sides.

Modeling of truss rods with a section from corners is performed in a work by Z. Deng [26].

Summarizing the results of the detailed analysis of the existing experience in the plates design and studies carried out with models of steel plates at the time of writing this work, we state the absence of clear results of modeling the operation of truss gusset plates for working conditions in the complex stress-strain state.

1.3. Statement of the research relevance

The relevance of the research topic is due to the fact that the existing regulatory, reference literature and scientific researches on the plates design quite fully developed methods for bending analysis under the action of moments, transverse loads and the combination of transverse loads and forces acting along the median plane, but the plates design for action of the longitudinal alternating load received little attention. There are tables for choosing the recommended thicknesses of gussets, but there are no design methods or documented researches substantiating these tables.

The presented work was done to fill the indicated gap.

1.4. Research goals and objectives

The main research goal is to establish the nature of the SSS distribution in the plates and to develop recommendations for the plates design.

To achieve this goal, the authors solved the following tasks:

- to classify by design the types of rods' junctions using connecting plates;
- to identify the types of nodes most common in practice for research;
- to perform the critical analysis of the existing experience in plates design for forces directed along the median plane of the plate;
- to develop design models of the investigated nodes for numerical research; perform design load cases and obtain stress fields;
- based on the results of factorial and regression analysis to derive dependencies that describe the nature of the change in the stress-strain state in the plate for the studied types of nodes;
- to develop recommendations for the design of the most characteristic types of nodes.

2. Methods

The gusset is in a complex stress-strain state (Fig. 1), significant local stresses arise in the zones of the elements' fastening due to the influence of the weld form and possible defects that are often found in the near-weld zone.

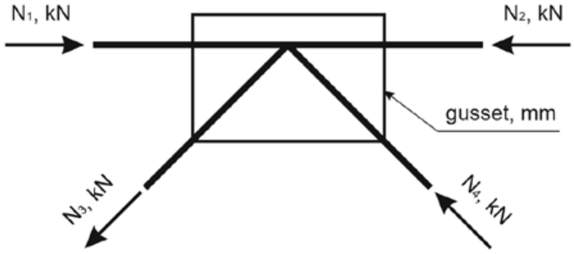


Figure 1. Gusset loading diagram by forces N from adjacent rods (N1 – N4 – rod forces).

The gusset operation is influenced by such features of the geometry of the heat-affected zone as defects in welded joints, concentration of stresses in the zones of holes and welds, initial curvatures, as well as the action of multidirectional forces.

In practice, four types of nodes are most common:

- symmetrical fastening of rods to gusset (Fig. 2, a);
- truss support node (Fig. 2, b);
- node of fastening the rack to truss belt (Fig. 2, c);
- node of fastening the braces elements to gusset with eccentricity (Fig. 2, d).

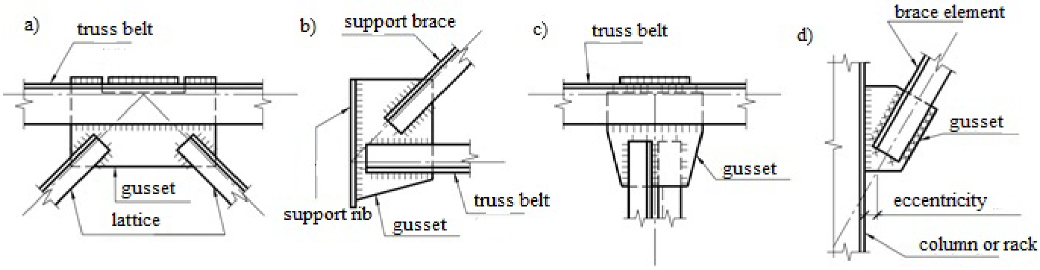


Figure 2. Types of nodes: symmetrical fastening of rods to the gusset (*a*); reference node (*b*); fastening of a rack to the truss belt (*c*); fastening of brace elements to columns and racks with eccentricity (*d*).

The research object is steel plates (gussets) connecting rods in hinged rod systems for the types of nodes shown in Fig. 2.

In this research using the finite element method implemented in Lira-SAPR software package, the nature of distribution of stress-strain state of truss gussets from paired corners is established depending on design solution of unit and value of acting loads. In the process the pattern of stress distribution in body of the gusset was assessed for four types of nodes of a symmetrical design solution: symmetrical fastening of rods, support node, post fastening node and eccentricity fastening node respectively. Was also analyzed the degree of influence of eccentricity's value on stress in gusset. Also sas determined the dependence of gussets' thickness on the maximum force in the attached rods and the subsequent conclusion about the level of safety margin. Subsequently, the thickness of the gussets was assigned not only based on the results of calculations, but also based on design considerations - the minimum design restrictions were taken into account in accordance with the requirements of regulatory documents (codes of rules).

The study was carried out on solid models of steel truss nodes. The main variable parameters are the configuration of the junction of the rods and the loads acting on the junction from the adjoining rods.

3. Results and Discussion

3.1. Research results of the work of trusses gussets with double-sided fastening of lattice elements

Material – mild steel with design yield strength of R_y = 240 MPa, modulus of elasticity E = 2.06×10^5 MPa, Poisson's ratio μ = 0.3.

The calculation of the steel trusses' nodes was performed in the software package Lira-SAPR. Rods and gussets were modeled by volumetric finite elements of the FE-36 type. Triangular volumetric finite elements were applied with an angle not less than 15°. The range of angles of lattice elements fastening was 30 – 60^0.

The load was evenly distributed over the cross-sectional area (Fig. 4). The load on the knots was taken according to the average values of forces from the intervals of values, according to which it was decided to take the thickness of the facings from the reference literature (intervals of forces are given in the header of Table 2 and Table 4). The cross-sections of the elements were taken on the basis of the bearing capacity to absorb the forces acting in them. The transition from the forces in the rods to the pressure on the loaded faces of the cross-sections of the rod models was carried out by the equation:

$$q_i = \frac{N_i}{A_i}, \quad (1)$$

where q_i is load in the form of pressure on the loaded cross-section faces of rod models; N_i is rod force; A_i is cross-sectional area of the rods.

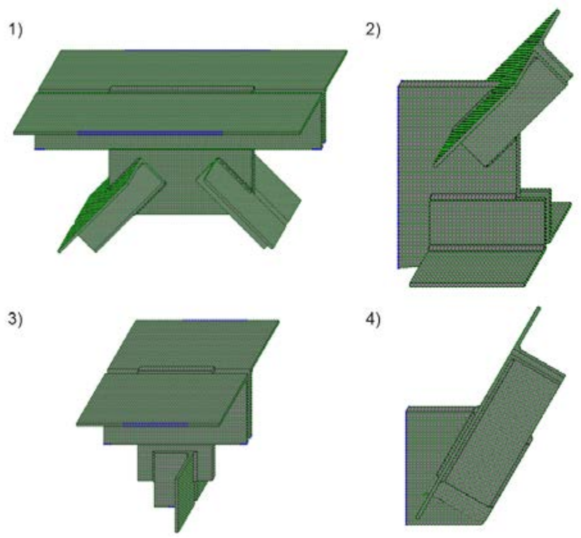


Figure 3. Finite element models of nodes: 1 – symmetric; 2 – support node; 3 – rack fastening; 4 – with eccentricity.

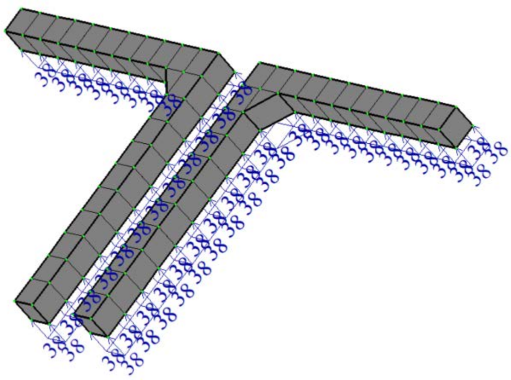


Figure 4. Model of load application (load, *q,* is given in MPa).

Considered the equivalent stresses variation in structural elements depending on the structural nodes solution. Fig. 5–8 show the isofields of equivalent stresses in the gusset for four types of nodes of symmetric design solution: symmetric fastening of rods, support node, fastening node of the rack and eccentric fastening of the brace, respectively.

According to the calculation results to determine the nature of the of stress fields distribution, gussets of trusses are separately identified. Diagrams with stress distribution in gussets of trusses for the studied design solutions of nodes are shown in Fig. 5–8. The analysis of the values of the reduced stresses in the trusses of the recommended thickness makes it possible to determine the value of the reserves under the action of the recommended values of the design forces.

To determine the actual load-carrying capacity of the truss beams, we corrected the values of design forces on the rods so that the stresses in the beams satisfy the condition $\sigma_{red} < R_y$ with a margin of 1–5 %. Based on the calculations results, built the diagrams for the dependence of the gusset thicknesses on the maximum force in the attached rods of models 1 – 4 and, accordingly, the obtained approximating dependences (2) – (5):

$$t_{f.1} = 17.36\left(1 - e^{-0.00251N}\right); \quad (2)$$

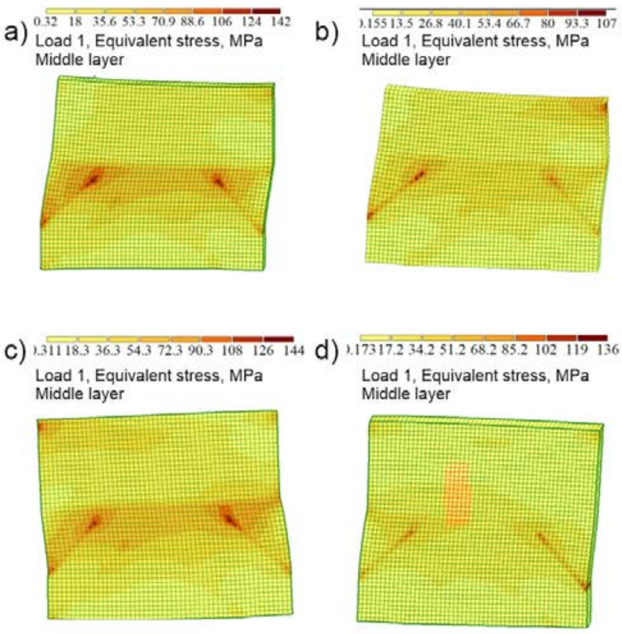
$$t_{f.2} = 17.04\left(1 - e^{-0.00261N}\right); \quad (3)$$

$$t_{f.3} = 14.44\left(1 - e^{-0.00373N}\right); \quad (4)$$

$$t_{f.4} = 16.46\left(1 - e^{-0.00292N}\right). \quad (5)$$

Note to formulas (2) – (5): force in kN, thickness of beams in mm.

Nomograms were obtained from the results of processing the data sets of a series of experiments on numerical models. Standard error: 0.15–0.18. Correlation coefficient: 0.98 – 0.99. The results obtained from the formulas are applicable for the force range from 150 to 2000 kN.



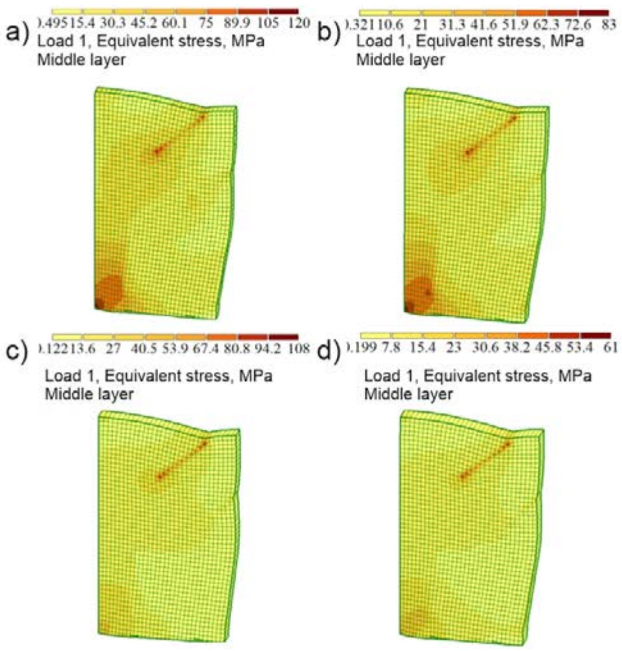
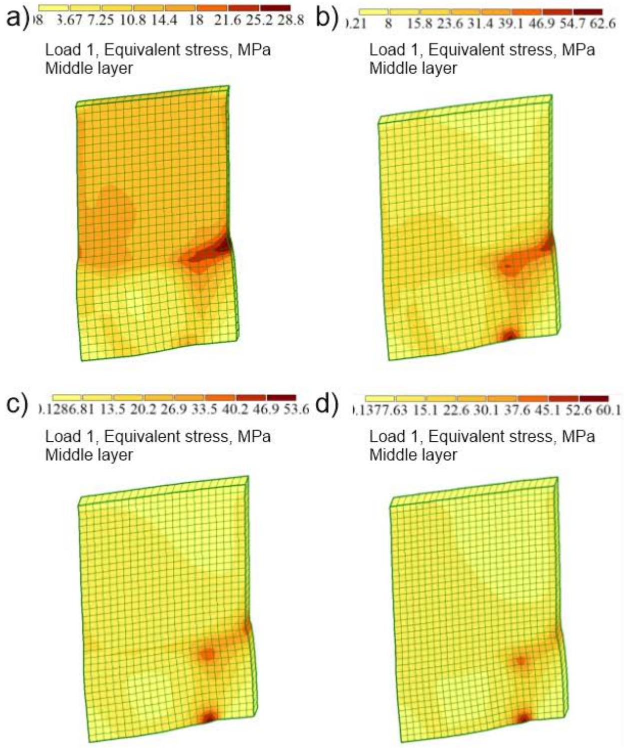


Figure 5. Isofields of equivalent stresses of finite element model for node type 1: a) t_f = 8 mm; b) t_f = 10 mm; c) t_f = 12 mm; d) t_f = 14 mm.

Figure 6. Isofields of equivalent stresses of the finite element model for node type 2: a) t_f = 10 mm; b) t_f = 12 mm; c) t_f = 14 mm; d) t_f = 16 mm.



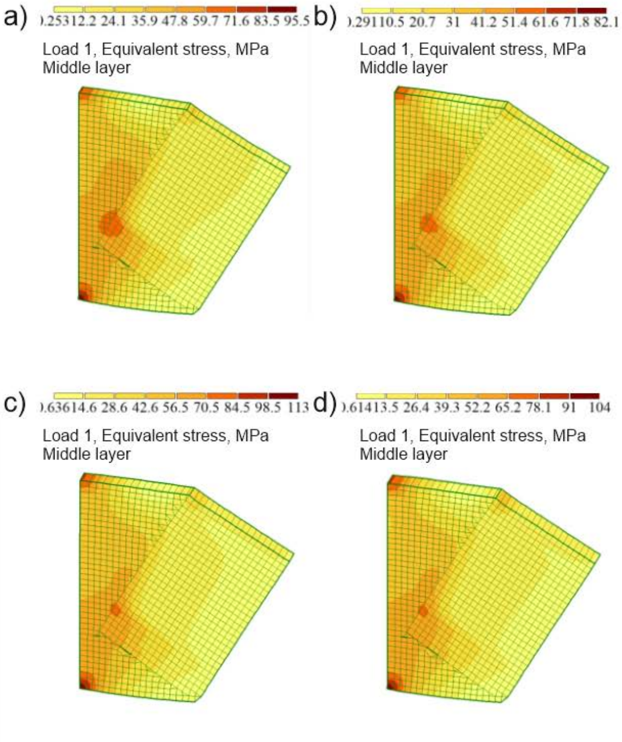


Figure 7. Isofields of equivalent stresses of the finite element model for node type 3: a) t_f = 6 mm; b) t_f = 10 mm; c) t_f = 12 mm; d) t_f = 14 mm.

Figure 8. Isofields of equivalent stresses of the finite element model for node type 4: a) t_f = 8 mm; b) t_f = 10 mm; c) t_f = 12 mm; d) t_f = 14 mm

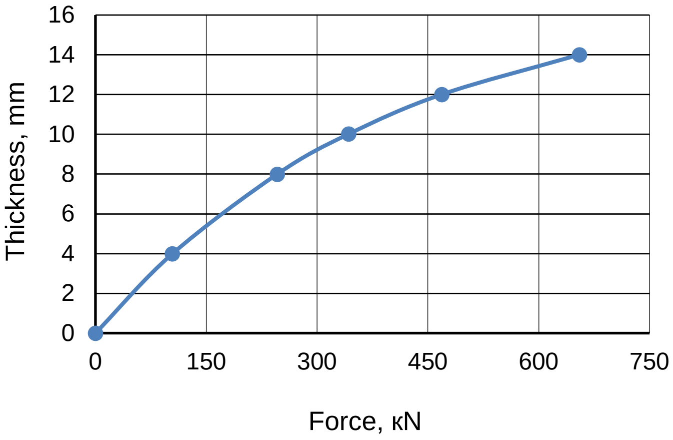


Figure 9. Dependence of the gusset thickness on the maximum force in the attached rods of the finite element model for node type 1.

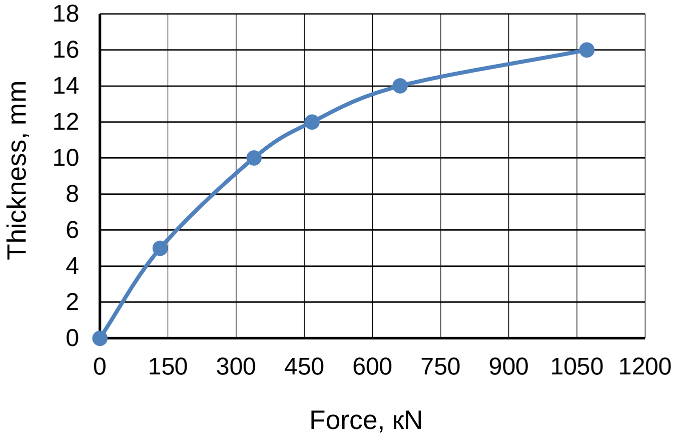


Figure 10. Dependence of the gusset thickness on the maximum force in the attached rods of the finite element model for node type 2.

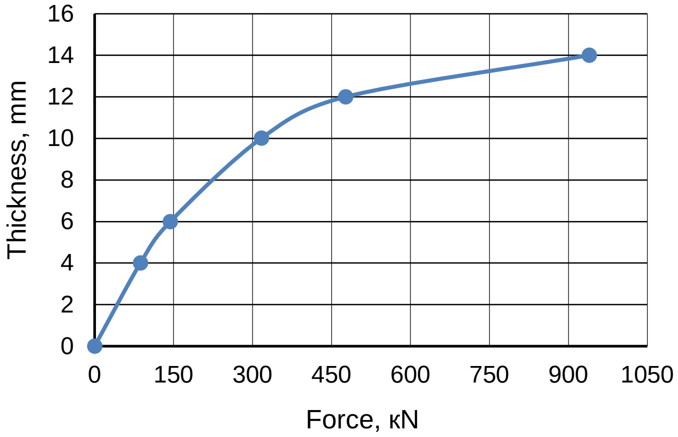


Figure 11. Dependence of the gusset thickness on the maximum force in the attached rods of the finite element model for node type 3.

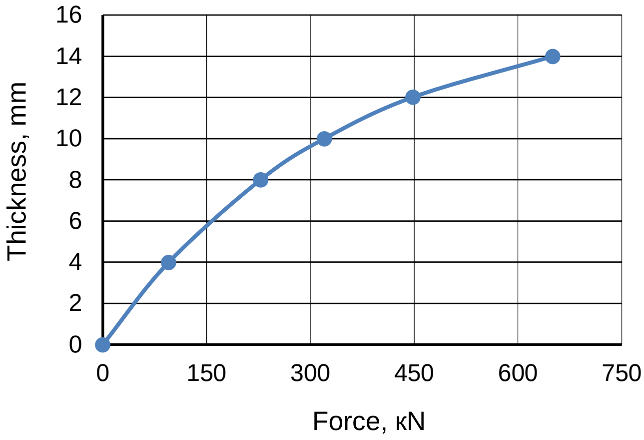


Figure 12. Dependence of the gusset thickness on the maximum force in the attached rods of the finite element model for node type 4.

The gusset thickness values were assigned not only based on calculations results, but also on the basis of design considerations: the minimum design restrictions were considered in accordance with the requirements of SP 16.13330.

Table 1. Stresses and safety factors for various nodes' types for a symmetrical design solution.

No.		Actual equivalent stress, MPa	Safety factor, %
1	1a	142.0	40.8
	1b	104.0	56.6
	1b	144.0	40.0
	1d	136.0	43.3
2	2a	120.0	50.0
	2b	83.0	65.4
	2c	108.0	55.0
	2d	61.0	74.5
3	3a	28.8	88.0
	3b	62.6	73.9
	3c	53.6	77.6
	3d	60.1	74.9
4	4a	95.5	60.2
	4b	82.1	65.8
	4c	113.0	52.9
	4d	104.0	56.6

Note to Table 1: design resistance R_y = 240 MPa.

The analysis of the results obtained allows us to conclude that the safety factors for each node model for the symmetric design solution are in the range of 40–88 %. Based on economic considerations, the thickness of the gusset can be reduced considering design constraints:

– for model 1 by 20 %;
– for model 2 by 30 %;
– for model 3 by 50 %;
– for model 4 by 30 %.

Table 2. Recommended gusset thickness values for symmetrical design solution.

Maximum force in rods of the lattice, κN	Up to 150	160 - 250	260 - 400	410 - 600	610 - 1000	1010 - 1400	1410 - 1800	More than 1800
Reference literature data, mm	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**
Thickness for node type 1, mm	5	7	8	10	12	13	15	16
Thickness for node type 2, mm	5	6	7	9	10	12	13	14
Thickness for node type 3, mm	4	4	5	6	7	8	9	10
Thickness for node type 4, mm	5	6	7	9	10	12	13	14

3.2. Research results of the work of trusses gussets with double-sided fastening of lattice elements

Trusses with one-sided fastening of lattice elements are trusses made of rods with a section of single corners.

Figs. 14–21 show isofields of equivalent stresses in the gusset plate for four types of nodes with one-sided fastening of lattice elements: for symmetric fastening of rods, support node, rack fastening node and eccentric link fastening node, respectively.

Figs. 14–17 show that when fastened with an offset to the corner, the gusset experiences overstress. In order to reduce the stress, in some cases the gusset is fastened end-to-end and the braces are placed on the corner (Fig. 13).

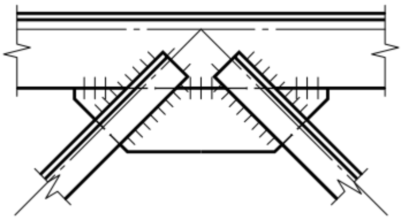


Figure 13. Fastening of the gusset end-to-end to the belt.

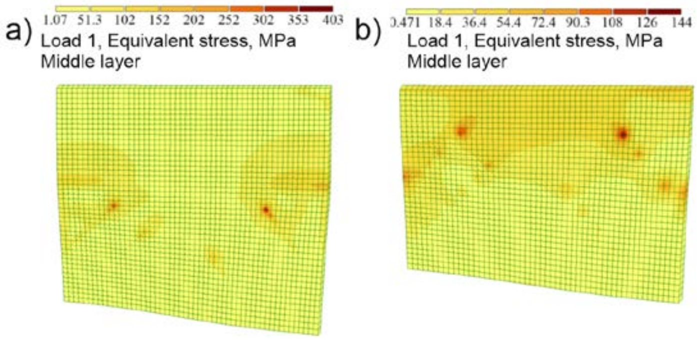


Figure 14. Isofields of equivalent stresses of the finite element model for node type 1a: a) t_f = 6 mm; b) butt gusset t_f = 6 mm.

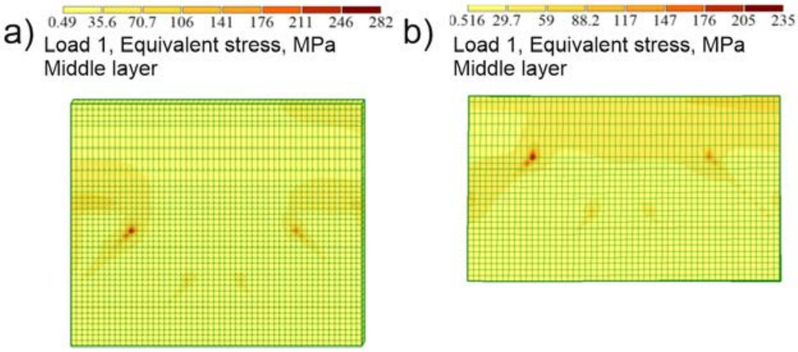


Figure 15. Isofields of equivalent stresses of the finite element model for node type 1b: a) t_f = 8 mm; b) butt gusset t_f = 8 mm.

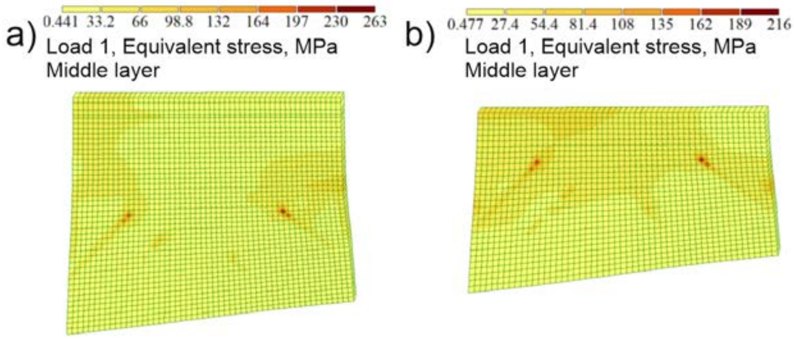


Figure 16. Isofields of equivalent stresses of the finite element model for node type 1c: a) t_f = 10 mm; b) butt gusset t_f = 10 mm.

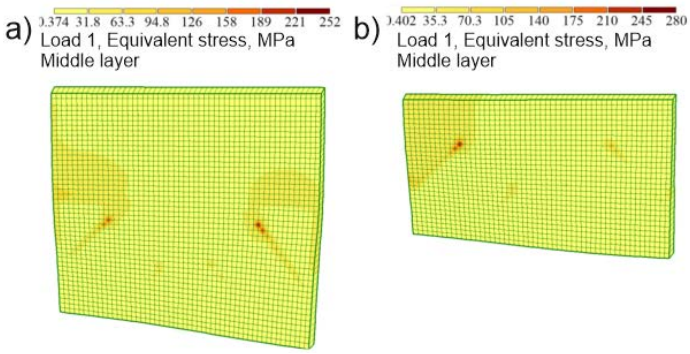


Figure 17. Isofields of equivalent stresses of the finite element model for node type 1d: a) t_f = 12 mm; b) butt gusset t_f = 12 mm.

For models 1a-1c (Fig. 14–16), butt-fastening completely solves the problem of overstressing. For model 1d (Fig. 17) butt-fastening does not solve the problem of overstressing, which is due to the small thickness of the corners of the chords. Local reinforcement of the chords is required to reduce stresses in the chords.

Fig. 18a shows the isofields of equivalent stresses for gusset of node type 2 with the recommended thickness t_f of 8 mm by Table 2.1. As you can see, the choice of this thickness leads to overstress, which is 16 %. By calculation the required thickness t_f is 14 mm (Fig. 18, b).

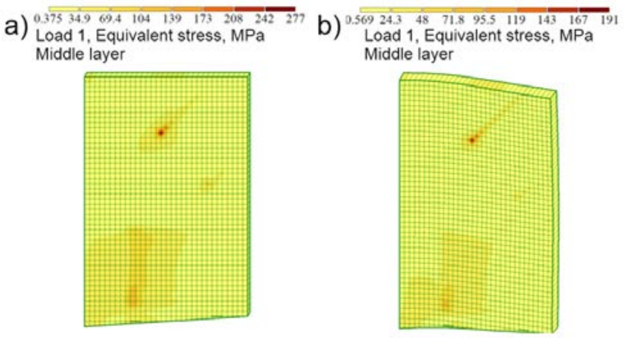


Figure 18. Isofields of equivalent stresses of the finite element model for node type 2, a: a) t_f = 8 mm; b) t_f = 14 mm.

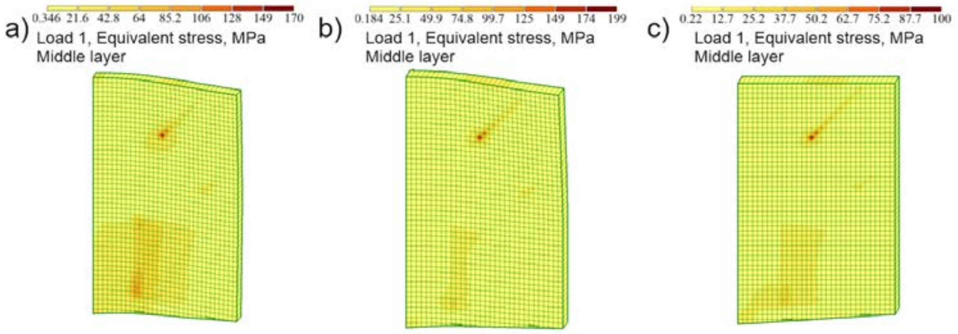


Figure 19. Isofields of equivalent stresses of the finite element model for node type 2, b-d: b) t_f = 10 mm; c) t_f = 12 mm; d) t_f = 14 mm.

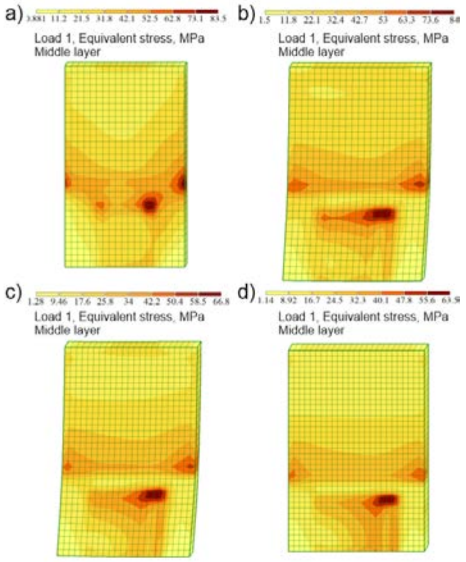


Figure 20. Isofields of equivalent stresses of the finite element model for node type 3: a) t_f = 6 mm; b) t_f = 8 mm; c) t_f = 10 mm; d) t_f = 12 mm.

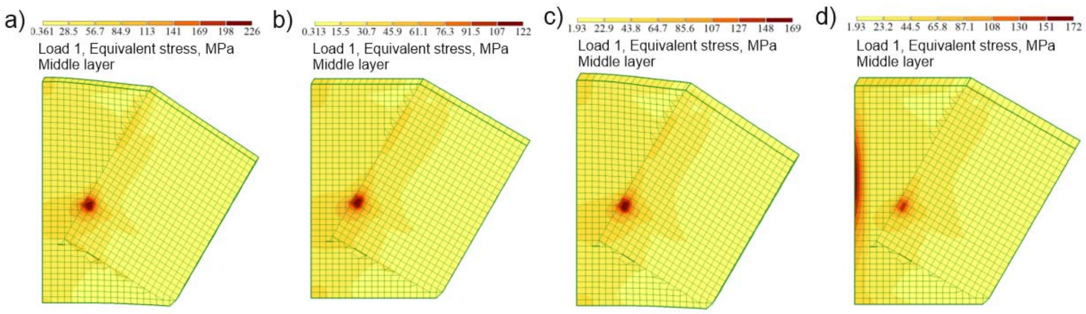


Figure 21. Isofields of equivalent stresses of the finite element model for node type 4: a) t_f = 6 mm; b) t_f = 8 mm; c) t_f = 10 mm; d) t_f = 12 mm.

Based on the calculations results, we built the diagrams for the dependence of the gusset thickness values on the maximum force in the attached rods of models 1-4 and, accordingly, the obtained approximating dependences (6) – (9):

$$t_{f.1} = 17.45\left(1 - e^{-0.00367N}\right); \quad (6)$$

$$t_{f.2} = 15.48\left(1 - e^{-0.00348N}\right); \quad (7)$$

$$t_{f.3} = 12.47\left(1 - e^{-0.00695N}\right); \quad (8)$$

$$t_{f.4} = 13.33\left(1 - e^{-0.00618N}\right). \quad (9)$$

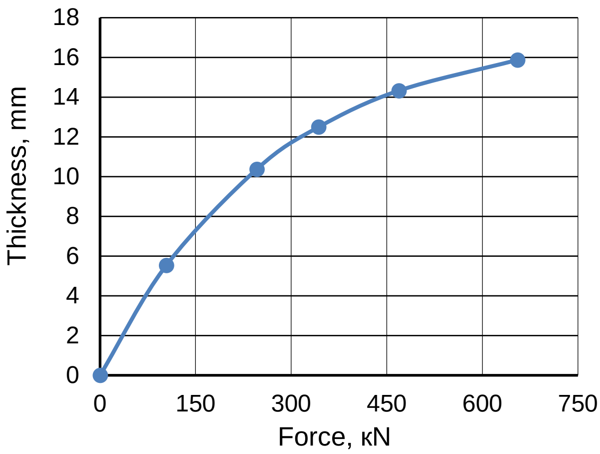


Figure 22. Dependence of the gusset thickness on the maximum force in the attached rods of the finite element model for node type 1.

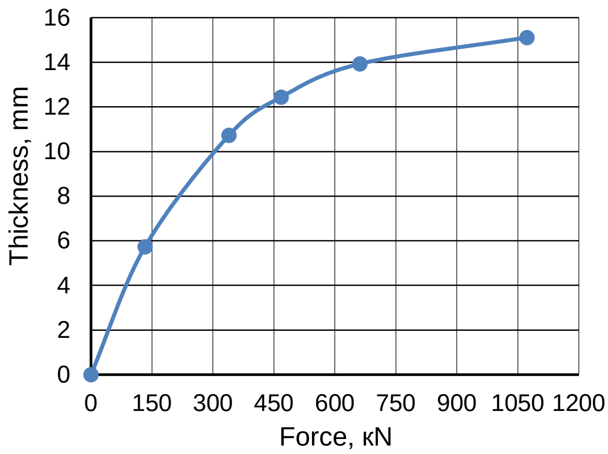


Figure 23. Dependence of the gusset thickness on the maximum force in the attached rods of the finite element model for node type 2.

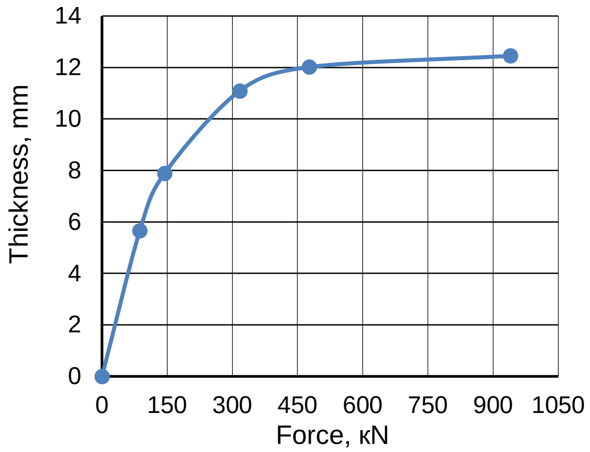


Figure 24. Dependence of the gusset thickness on the maximum force in the attached rods of the finite element model for node type 3.

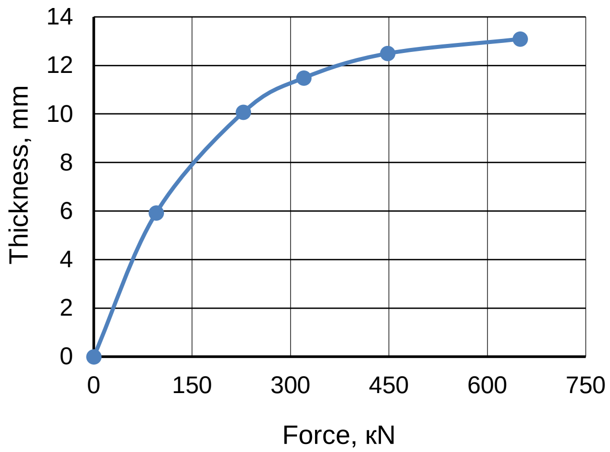


Figure 25. Dependence of the gusset thickness on the maximum force in the attached rods of the finite element model for node type 4.

Table 3. Stresses and safety factors for various types of nodes for asymmetrical design solution.

No.		Actual equivalent stress, MPa	Safety factor, %
1	1a	144	40.0
	1b	235	2.1
	1c	216	10.0
	1d	280	–16.7
2	2a	191	20.4
	2b	170	29.2
	2c	199	17.1
	2d	100	58.3
3	3a	83.5	65.2
	3b	84	65.0
	3c	66.8	72.2
	3d	63.5	73.5
4	4a	226	5.8
	4b	122	49.2
	4c	169	29.6
	4d	172	28.3

Note to table 3: design resistance R_y = 240 MPa.

The analysis of the results obtained allows us to conclude that the safety margins for the types of nodes 1 and 2 of the design solution with one-sided fastening of the lattice to the belt are insufficient. Thus, the gusset thickness, taking into account design constraints can be reduced:

– for model 3 by 40 %;
– need to increase:
– for model 1 by 40–60 %;
– for model 2 by 20 %.

Table 4. Recommended gusset thickness values for asymmetrical design solution.

Maximum force in rods of the lattice, кN	Up to 150	160 - 250	260 - 400	410 - 600	610 - 1000	1010 - 1400	1410 - 1800	More than 1800
Reference literature data, mm	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**
Thickness for node type 1, mm	10	12	14	16	18	20	22	24
Thickness for node type 2, mm	7	9	11	13	15	17	19	21
Thickness for node type 3, mm	4	5	6	8	9	10	11	12
Thickness for node type 4, mm	5	6	7	9	10	12	13	14

The improved method for selecting the gusset thickness:

1. To calculate the truss, determine the forces in rods.
2. According to the greatest force, depending on the node type and the design solution, select the required gusset thickness from Tables 2 or 4.

2.1. Research results of the gussets' work of brace elements fastening with eccentricity

A study was performed on the influence of the eccentricity value on the stress in the gusset. The main variable parameter is the displacement of the attached element relative to the axis of the abutment of elements.

Based on the calculations results, we made graphs of the dependence of the change in stresses of the gusset relative to the value of the abutment eccentricity and obtained the approximating dependences.

Dependence of stress change for 10 mm thickness of the gusset:

$$\sigma_{f.10} = 1.432 + 1.707 e_x - 4.789 \cdot 10^{-3} e_x^2. \quad (10)$$

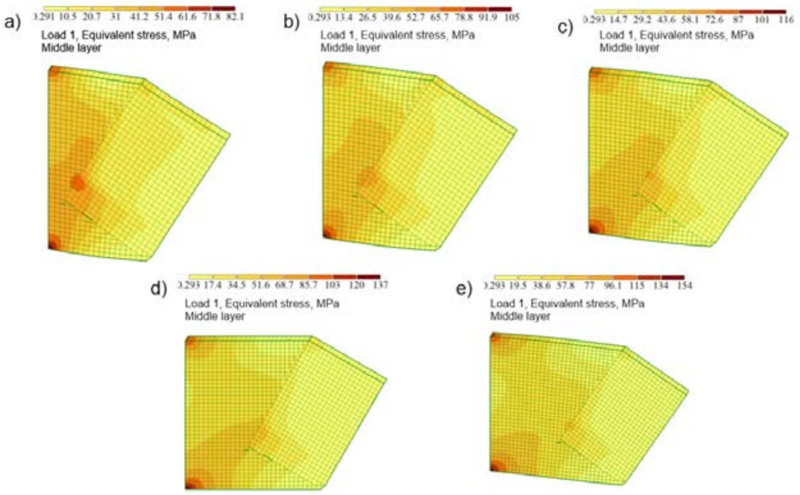


Figure 26. Isofield of equivalent stresses for node type 4 with the gusset thickness t_f = 10 mm and the value of the eccentricity: a) 50 mm; b) 75 mm; c) 100 mm; d) 125 mm; e) 150 mm.

When constructing the graphs, the reduced stresses were taken at a distance of one thickness from the edge of the attachment, which takes into account the catheters of the weld.

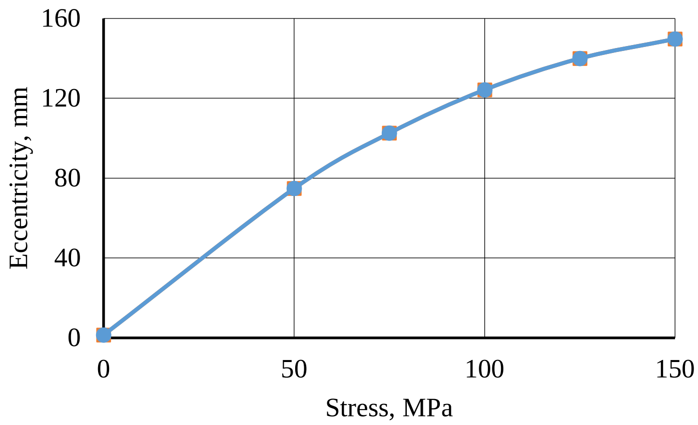


Figure 27. Dependence of the displacement influence on stress for the gusset thickness t_f = 10 mm.

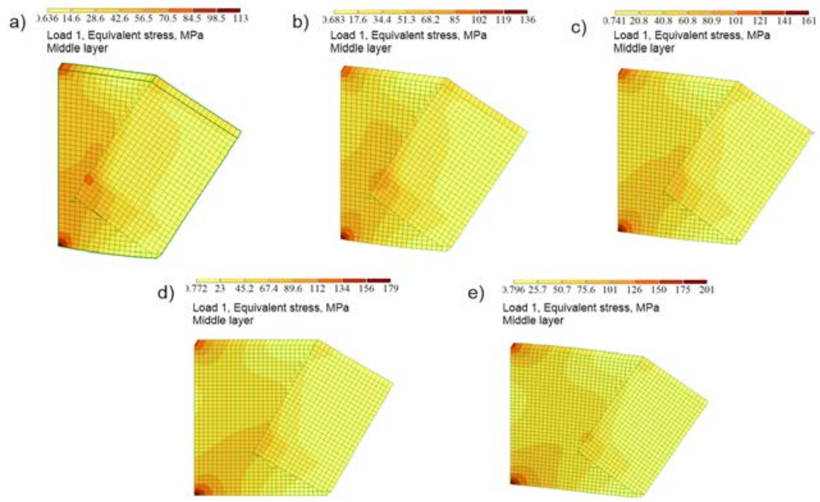


Figure 28. Isofield of equivalent stresses for node type 4 with the gusset thickness t_f = 12 mm and the value of the eccentricity: a) 50 mm; b) 75 mm; c) 100 mm; d) 125 mm; e) 150 mm.

Dependence of stress change for 12 mm thickness of the gusset:

$$\sigma_{f.12} = 1.883 + 2.347 e_x - 7.055 \cdot 10^{-3} e_x^2. \quad (11)$$

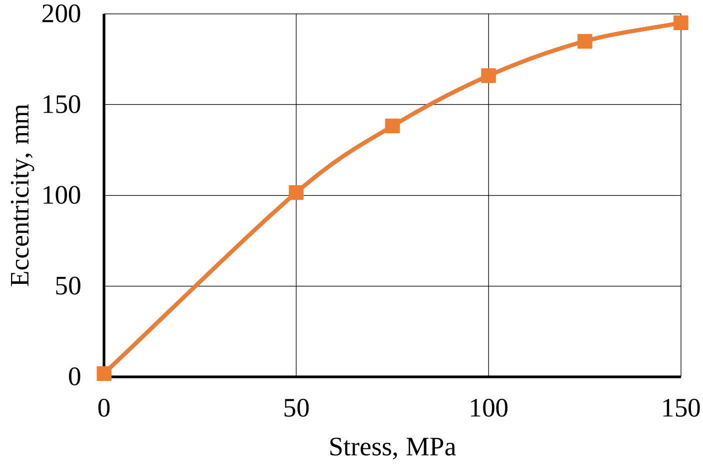


Figure 29. Dependence of the displacement influence on stress for the gusset thickness t_f = 12 mm.

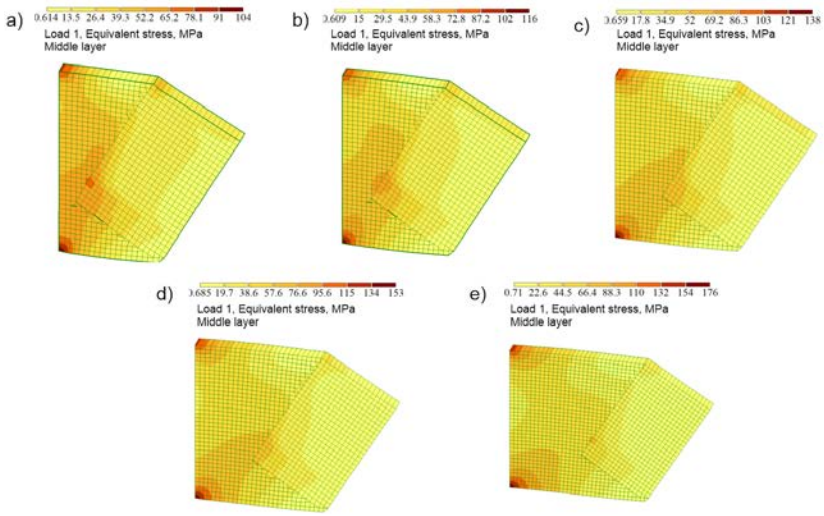


Figure 30. Isofield of equivalent stresses for node type 4 with the gusset thickness t_f = 14 mm and the value of the eccentricity: a) 50 mm; b) 75 mm; c) 100 mm; d) 125 mm; e) 150 mm.

Dependence of stress change for 14 mm thickness of the gusset:

$$\sigma_{f.14} = 3.611 + 1.841 e_x - 6.264 \cdot 10^{-3} e_x^2. \quad (12)$$

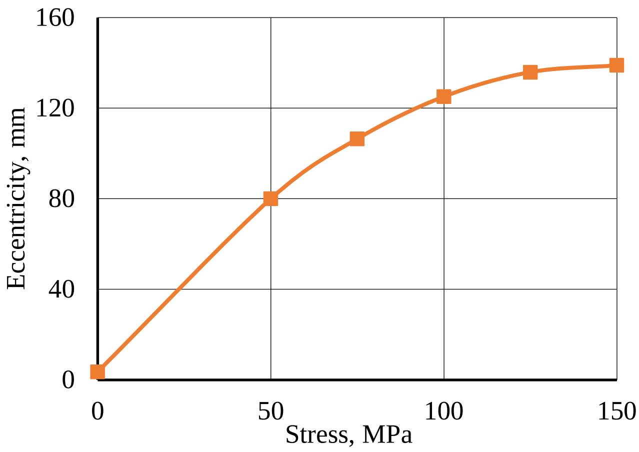


Figure 31. The dependence of the effect of displacement on stress at the thickness of the gusset plate t_f = 14 mm.

The diagrams show that the nature of the change in the stress-strain state in gussets with constant thickness during increasing eccentricity values is described by a quadratic function.

When carrying out practical calculations and design of steel structures, the engineer can assign the gusset thickness, having the initial knowledge about the value of the force acting from the side of the rods, the node type and the possible displacement when fixing the element.

For intermediate values of the initial parameters the gusset thickness can be determined by linear interpolation.

A comparison of the results of this study with the results presented in the reference literature is given for symmetrical sections and for asymmetric sections in Table 2 and Table 4, respectively.

Table 2 data analysis shows that the thickness values of gussets recommended for use by the reference literature are overestimated on average for various types of nodes from 21 % to 94 %, which leads to a significant overspending of the material when applying recommendations for the construction of building roofing. Knowing that the weight of gussets is 25–30 % of the total weight of steel trusses, the use of optimal values of gusset thickness substantiated by the research will reduce the metal consumption of trusses by 35–40 %.

Table 4 data analysis shows that the thickness values of gussets recommended for use by the reference literature are underestimated on average for the first two types of nodes by 20–60 %, which can lead to failure of the structure as a result of the exhaustion of the bearing capacity.

To increase the load capacity of nodes using a single corner, it is recommended to use butt plates.

In order to achieve the tasks of using efficient and rational structures in the field of steel construction it is necessary to amend the regulatory documents in terms of including the methodology for calculating the plates of truss gussets and introduce the specified thickness values recommended for use as truss gussets with rods of symmetrical and asymmetric sections into the new editions of the designer's reference books.

4. Conclusions

1. The authors analyzed trusses' gussets under load for constructive solution with two-sided and Tone-sided fastening of lattice elements for four characteristic types of nodes. Their stress-strain state was investigated depending on the value of the acting loads to the node and on the rod interface configuration.

2. It was established that the safety factors, depending on the type of unit of the structural solution with two-sided fastening of the lattice elements, are more than 40 %. This allows reducing the gussets' thickness taking into account design constraints.

3. It was established that the safety factors for node type 3 of structural solution with one-sided fastening of the lattice elements are 7–90 %. This makes it possible to reduce the gusset thickness for node type 3. The calculation results showed that for node types 1, 2, and 4, gussets are characterized by overstress, which requires an increase in thickness, taking into account design constraints.

4. We analyzed the influence of the eccentricity value on the stress in the gusset. It was determined that the main parameter influencing the stress-strain state of the gusset is the displacement of the attached element relative to the axis of the elements abutment. We derived dependences and made diagrams of the displacement influence on stress for different values of gusset thickness.

5. The obtained data can be used in the design of new structures and in assessing the bearing capacity of structures in operation.

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