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Research paper

Innovative Combined Truss: Experimental and Numerical Research

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Abstract

In the article, based on the analysis of modern trends in the development of construction in the world shown, that the problem of increasing the competitiveness and efficiency of building steel structures is relevant. Conducted research of steel combined structures confirmed, one of the effective methods for solving this problem is the use of a calculated method for regulating the stress deformation state (SDS) in steel metal structures during the design process. It does not require any additional material costs and allows you to design equally stressed structures as the most rational systems. The results of experimental research of a metal-wooden truss 12 m spans with the calculated SDS regulation during the design process are presented. Experiment results data, reflecting the real work of a metal-wooden truss, satisfactorily agree with the theoretical. Experimental studies confirmed the hypothesis of the possibility of regulating the stress deformation state of combined structures with elastic-supportive supports and the achievement of an stress equality state in the calculated sections. A numerical experiment was conducted for a combined steel sprengel truss with a span of 18 m. Rationalized, in terms of material costs, height of a sprengel truss, the angles of inclination of the compressed rods of the grating of the truss and the strength of the reinforcement system. Examples of implementation of such rational structures are given.

Keywords: *Combined metal-wooden truss, calculation method of regulation, experimental and numerical research*.

1. Introduction

Scientific and technological progress around the world is associated with the creation and development of new structures forms, including building structures. This should ensure that, on the one hand, efficiency and quality of designing of new structures, and on the other hand - saving materials and reducing labor costs. To the number of questions, where the improvement of constructive forms and methods of their calculation can give tangible practical results, questions include, which are connected with steel, metal-wooden structures of cover, overlappings and bridge transitions.

Recently, designers, due to certain technological complexities, are increasingly abandoning previous tensions by replacing their estimated redistribution efforts and regulation of the stress deformation state (SDS) of structures. The idea of such regulation is to provide a pre-selected rational distribution of efforts in the elements by adapting the design parameters to a definite end result [1-4].

First of all, it is about variation of geometric and rigid characteristics of cross sections of elements, geometric and topological characteristics of systems and parameters of boundary conditions. Such techniques allow to reduce the estimated efforts in some elements (sections) of the structure due to increased efforts in other elements (sections) and design equally stressed structures as the most rational systems [9,12,16-18].

As the criterion of rationality stands the energy criterion of rational design, as well as the requirement to provide stress equality in the calculated sections. Disclosure of potential regulation calculation method, which is in the combined systems, creates the basis for the development of scientific foundations for the acquisition of new generation structures.

The problem posed to the greatest extent correspond to combined (spindle, cable, hanging) structures of cover and overlappings, the main working element of which is the beam of rigidity, the metal-tightness of which largely depends on the technical and economic performance of the entire system.

It is the conditions for designing the beam of rigidity that allow the regulation of effort throughout the system. In many cases, combined structures have a number of advantages over traditional ones, the main of which is the concentration of materials and the possibility of designing them with small-elements [5,8,13].

Existing methods of calculating such systems give an uneven tense state along the length of the main element - beam of rigidity. This makes the existing combined structures not always rational [8,14,15]. Therefore, the improvement of the calculation method of combined steel structures, which would reflect their real work and ensure rationality, is currently a topical issue.

Today, sufficient theoretical and experimental research have not been carried out, which would provide the design of rational combined steel structures in accordance with modern requirements.

2. The main material

To calculate rational combined steel structures, the energy-variation Lagrange method is proposed, within the limits of its minimization in an improved version of the displacement method [9,11]. The essence of the calculation: first, based on the method of decomposition of the system, divide the system into two subsystems - the main and auxiliary [3]. The main subsystem is a beam of stiffness on elastic supports, which are modeling the reinforcement system. Elastic supports are elements (vertical and inclined) of the combined structure (system). Auxiliary subsystem is the construction of a sprengel. In this case, not static principles, but energy-variational, in particular the Lagrange principle, were used for the calculation. Further, using the synthesis of the system, we count its stress deformation state. For the proposed calculation model, the mathematical model is described on the basis of the total potential energy of the system [2,9]. The most rational areas for using such structures are spans from 6 to 60 m.

2.1. Experimental research

The purpose of the research is a metal-wooden truss span of 12 m was the examination of the proposed method of SDS regulation. The research objectives were as follows:

- to investigate the stress deformation state and to determine the quantitative parameters of the regulation of SDS during loading;
- measurements of vertical displacements at characteristic points;
- measurement of the values of fibrous deformations in characteristic sections.

2.1.1. Subject of research. Structural parameters of the investigated truss

For the test, a structures of a metal-wooden truss (MWT) was made with a span of 12 m. The upper belt of the truss (made of steel double-leaf paired channels No. 10) is designed as a metal non-split beam on five pillars, in particular on three (medium) elastic supports (Figure 1). The truss is designed so that in the upper belt, which rests on the elastic-supporting supports, the effort was regulated during the loading process in order to equalize the stresses in its calculated sections, as a non-split beam.

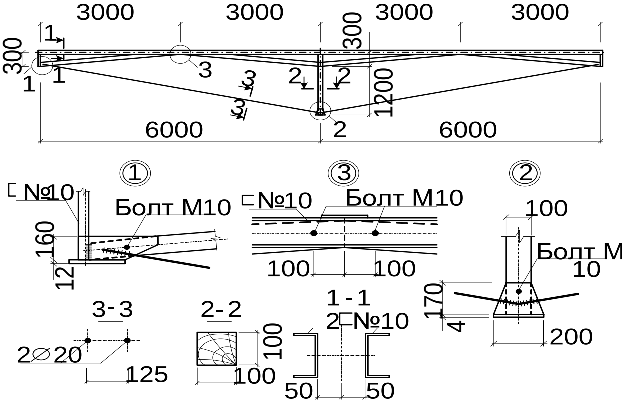

Fig.1: Structure of an experimental sample of a metal- wooden truss and knots 1, 2, 3

As you know, wood has considerable strength when working along fibers. However, due to anisotropy, it is much weaker working across the fibers, which leads to a low resistance to the cut (R = 1.3-1.5 MPa). At the same time, the strength of the steel on the cut is about 150 MPa, which is two orders higher than a wood. Since the strength of the tree is compression, it is attributed to the bulk weight $R_{cw} / \rho = 15/0,06 = 250$ is approaching the corresponding relation for steel $R_y / \rho = 210/0,78 = 269$, then we can replace elements in steel structures, which work on compression, wooden elements [2]. These properties were used when creating a metal-wooden truss with a span of 12 m (Figure 1). Truss to be tested is a small element, in which an average rack and two pairs of slats - wooden beams with a section of 100 x 100 mm (Figure 1), since they operate under the action of external compression only. The geometric scheme of the truss, the distribution of effort in it, made it possible to perform the lower belt (metal spregnel) from a steel round section d = 20 mm. Splits in the upper nodes are connected to the upper belt of the truss. The lower extremity ends of the slopes belong to the support nodes of the structures, medium - connected in a central node with a rack, which, respectively, at the top and bottom ends is connected to the upper steel belt and metal sprengel.

Diagonal webs unload the upper belt from compression efforts. Its discharge is due to the location of the diagonal webs in the structures so that, that the junction of their ends with the central rack is located about (0.3 m) from the upper belt, and the nodes of the connection between them coincide with the nodes of their connections with the upper belt in the quarters of the span.

The lower extremes of the slip are in turn the corresponding elements, which are connected in the supporting nodes of the model, short supporting steel racks which are connected to the upper belt. Consequently, the basic nodal joints of the upper belt provide its work, as an non-split 4-span beam on elastic supports.

The upper belt of the experimental model of 12 m span was designed from two pairs of steel channels No. 10 outside the shelves. Such a fairly small height of the section of the upper belt was due to the characteristic feature (ease) of the structures, the upper belt of which worked as an uncut bar on elastic supports. Nodal combinations of slices and upper belt have metal shapes that reliably fix the wooden slopes. Test results of steel standard samples, cut out rolling, from which made experimental models, had average values of the yield strength of 282-284 MPa.

Standard wood samples for compression and bending were made from cut bars, used for the production of an experimental sample of a metal-wooden truss (three samples from each bar, see Table 1). The compression samples were made in the form of a rectangular prism with a base 20x20 mm and a length of 30 mm along the fibers, and samples on the deflection - in the form of a rectangular bar 20x20x300mm. The moisture content of the samples was approximately 12%.

Table 1: Results of laboratory tests of standard samples of wood

S.No	Strength, MPa		Module elasticity MPa (10^3)
	compression	bending	
1	38,3-42,6	44,8-50,2	9,6-12,1
2	37,4-40,2	43,6-46,7	10,8-11,6
3	40,8-44,6	52,9-57,8	11,6-13,8
4	40,3-42,4	51,3-54,9	10,4-12,6

Testing of samples of wood on compression was carried out on a machine P-5 at a scale of force measuring 25 kN in a device with a ball-shaped support, and samples of wood on the bend - on the same machine at the scale of 5 kN in the device with a distance between the centers of the supports 240 mm and between the centers loading the leg 120 mm.

In determining the strength of the speed of movement of the head of the machine was 4 mm / min. To determine the modulus of elasticity, the deformation was measured with indicators of the clock type IR-0.01, fixed in the clamps on the neutral axis of the sample.

2.1.2. Test bench and equipment

A special booth was designed and manufactured for testing the fixed in concrete foundations, as well as traverse and vertical traction systems, fixed by anchors in the floor (Figure 2). The loads were transmitted evenly distributed by the length of the upper belt by six hydrodrals. All jacks were connected to one hydraulic system, through which the load was transferred to the structures.

The load to the upper belt (non-split beam on elastic supports) was transmitted at 11 points, which maximally approximated it to a uniformly distributed (Figure 2). The truss in the knots was fixed from the bending plane by vertically pliable horizontal ties, which did not interfere with the vertical movement of the upper belt and the structures knots in general.

Vertical displacements were measured by forgynometer, fibrous deformation in its characteristic places of rods and nodes - glued on them strain gauges on the basis of 20 mm. Together, ten forgynomete were installed and 82 strain gauges stuck, which gave an opportunity to estimate SDS in 14 cross-sections of elements, in particular in the 8 transverse sections of the upper belt. Impressions strain gauges were registered with strain gauge equipment type AID-2m with switching device. The general view during the test is shown in Figure 2, and nodes on Figure 3.

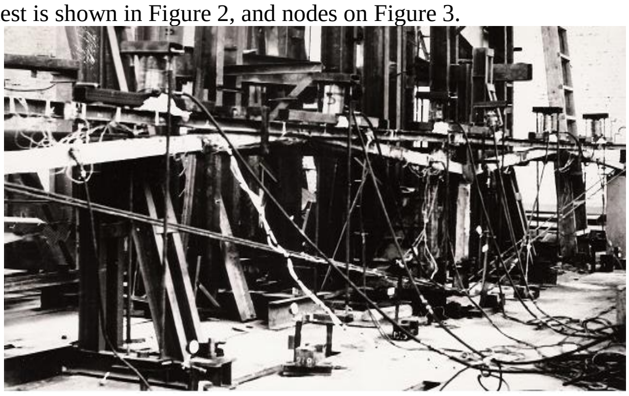

Fig.2: A general view of a metal-wooden truss with a span of 12 meters

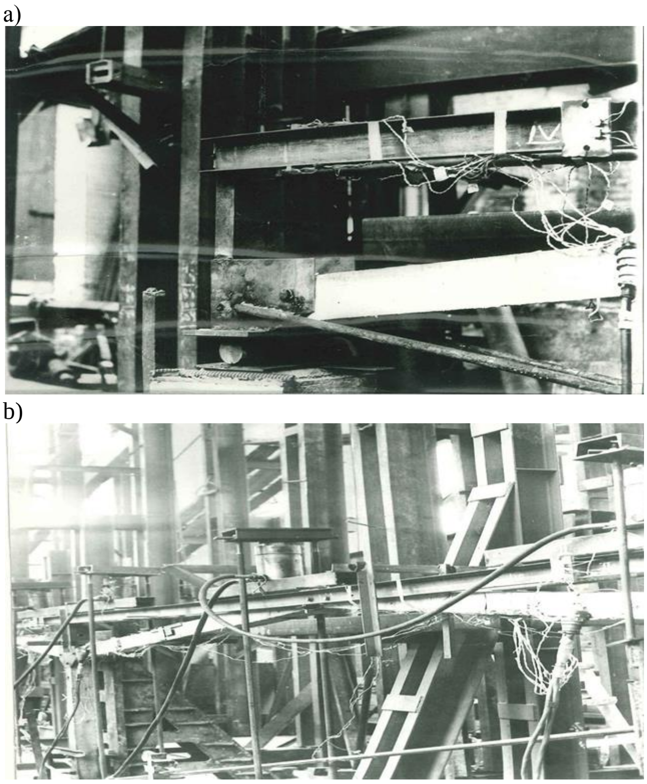

Fig.3: Tests of a metal–wooden truss with a span of 12 m: a - a supporting knot; b - nodes transferring the load on the upper belt by six hydrodrals

2.1.3. Results of experimental studies

The main results during the testing of the experimental model were vertical deflections (f) and relative fibrous deformations (ε) in the characteristic locations of the elements on the bases of the strain gauge are shown in Figure **3**–6. The load on the experimental model was created in four cycles with subsequent unloading after the next cycle. The size of the regulatory load was 2.4 kN / m, 3.5 kN / m - estimated and 4.0 kN / m - was 1.14 calculated.

During the first load cycle from 0 to 2.4 kN / m, the experimental deflection increases linearly to a load level of 1.2 kN / m. Further, after full unloading (only the load on the truss own weight is left and auxiliaries and appliances) in case of reload (second cycle) the linear law of the height of the deflection is maintained up to a load of 2.4 kN / m (Figure **4**).

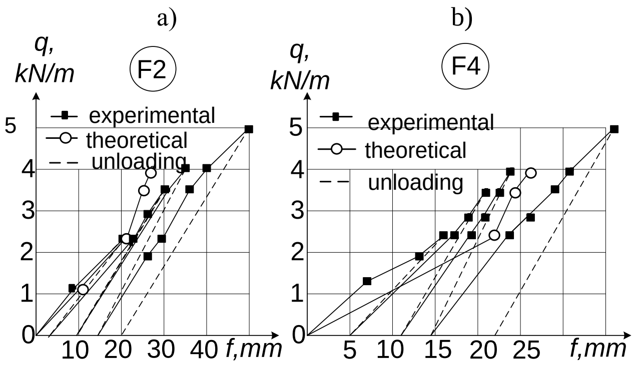

Fig.4: Charts of deflections of a metal-wooden truss with a span of 12 m: (a and b) in the places where forgynometer are installed F2, F4 (theoretical and experimental)

During the third load cycle, the linear law of deflection development remains at the same level of load: as in the second cycle (up to 2.4 kN / m). In the case of a further increase in the load of the third cycle, the increase of deflections gradually deviates from the linear law with a significant increase in its intensity, since reaching the load level of 3.7-4 kN / m. Worth noting, that the discharge indicated on the graphs (Figure 4,5) by dashed lines, occurred continuously with a slow decrease in its level.

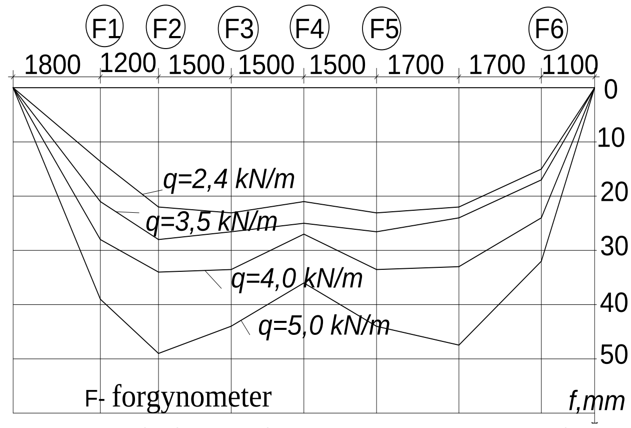

Fig. 5: Depths of deflections of metal – wood truss with a span of 12 m

After each load cycle, residual deformations were observed, the value of which increased after each successive cycle. At all stages of the load, the value of residual deformations did not exceed 2.5-4.5%. The reason for this was the bypass of wood in the knots. Vertical deflections of the experimental sample under loads, up to those, preceding the boundary, had an elastic character (Figure 4).

Boundary bearing capacity of the investigated structure was determined by a sharp increase in deflection during the application of the next degree of external load, after which the test was stopped.The largest deflections were observed in ¼ span, which is explained by the greater pliability of elastic support in these places, compared with the middle of the span in the place of the central riser (Figure 5).

As can be seen from the diagram of the deflections of the truss (Figure 5), the deflection in the left fourth flight (forgynometer F-2) from the standard load is 22.1 mm, that for half the truss *(l* / 2 =6 m) is 1/271 length of its half, and for the whole truss twice less, that is 1/542 *l* (Table 2), which is 2.17 times less than the standard stipulated 1 / 250 *l* = 48 mm [10].

As can be seen from Table 2, the theoretical deflection from the normative loading in the middle of the span of the truss (F4) is 23.87 mm higher than the maximum experimental deflection in the left fourth flight (forgynometer F-2) - 22.1 mm by 8%, which provides a stock of strength and stiffness of the structures.

Table 2: Deflections of a metal - wooden truss by span *l* = 12 (forgynometer F2)

Load in kN / m	Deflections in mm					$[(f_e - f_T)/ f_e] \cdot 100$ %
	Experimental			Theoretical		
	Absolute, mm (F2)	Relative		Absolute, mm (F4)	Relative	
		For half the truss	For the whole truss		For the whole truss	
	f_e	$f_e / l/2$	f_e / l	f_T	f_T / l	
2,4	22,1	1/271	1/542	23,87	1/503	- 8,0*
3,5	29,2	1/205	1/410	24,81	1/484	15,1
4,0	35,5	1/169	1/338	26,76	1/448	24,6
5,0	49,14	1/124	1/248	-	-	-

*The difference between the theoretical and experimental data is explained by the crumple of wood in the nodes of the truss

When increasing the load on the truss (through the crumple of wood in the nodes of the truss), the theoretical deflections in the middle of the truss span (F4) become less experimental in the fourth left span (forgynometer F-2) and the maximum discrepancy is in the range of 15.1 – 24.6%. The difference between the is in the range of 15.1 – 24.6%. The difference between the theoretical and experimental deflections in the middle of the span of the truss (forgynometer F4) is within the range of 10.1 – 44.6% (Table 3).

Table 3: Deflections of a metal – wooden truss by span *l* = 12 (forgynometer F4)

Load in kN / m	Deflections in mm				$[(f_e - f_T)/ f_e] \cdot 100$ %
	Experimental		Theoretical		
	Absolute, mm (F2)	Relative	Absolute, mm (F4)	Relative	
		For the whole truss		For the whole truss	
	fe	f_e / l	f_T	f_T / l	
2,4	16,5	23,87	1/503	1/503	- 44,6*
3,5	20,4	24,81	1/484	1/484	-21,6
4,0	24,3	26,76	1/448	1/448	-10,1
5,0	36,8	-	-	-	-

*The difference between the theoretical and experimental data is explained by the crumple of wood in the nodes of the truss

Here, the theoretical deflection is greater than the experimental at the normative load, and when the load increases, the divergence decreases to 10.1%. Consequently, the results of the calculations are satisfactorily consistent with the experimental data. The boundary state of the experimental sample of a metal- wooden truss corresponded to the formation of cracks in the supporting slopes.In order to assess (Figure 6,7) the possibility of the calculation of SDS regulation in the beam of stiffness - equalization of the calculation of SDS regulation in the beam of stiffness - equalization of stresses, measured during deformation tests graphs compressed zones in the beam of hardness of a metal–wooden truss from the magnitude of the uniformly distributed load q in kN/ m, as well as the distribution of fibrous deformations ε x10^{-5} at the estimated load of 3.5 kN / m in the characteristic cross sections of the beam of rigidity of the truss. From the graphs it is seen that the maximum fibrous deformation have close values(within 5-17%), both in the stretched and in the compressed zones.

In order to more clearly compare fibrous deformations on the basis of Figure 6,7 in the characteristic run and support sections (1-1,2-2 and 3-3) of the incisional upper, stuck on an elastic-pleasing support, give the data in the form of Table 4

Table 4: Fiber deformations ε x10^{-5} in the beam of rigidity of a metal–wooden truss at a calculated load of 3.5 kN / m

Section number	Maximum fibrous deformation ε $x10^{-5}$		Difference in %
	compression	stretch	
1-1	76,8	-	0
2-2	80,0	-	4,2
3-3	88,8	-	15,6

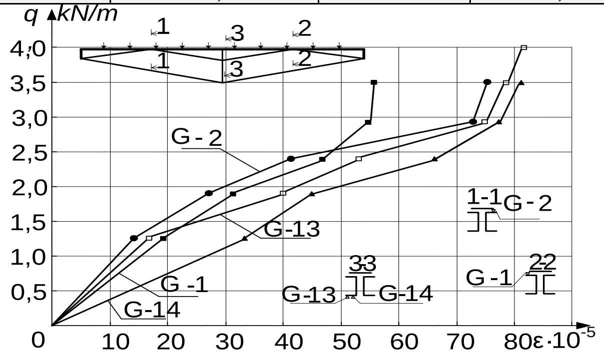

Fig. 6: Graph of fiber strains of strain gauges G-1, G-2, G-13, G-14 in stretched zones

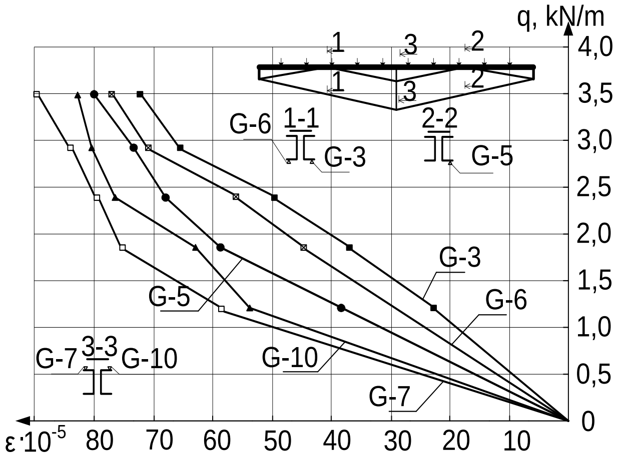

Fig. 7: Graph of fiber strains of strain gauges G-3, G-6, G-7, G-10 in compressed zones

As can be seen from Table 4, at the estimated load q = 3.5 kN / m, fiber deformations in the calculated sections of the upper indiscriminate belt of the farm were slightly different among themselves. The difference was up to 15.6%. This maximum discrepancy is consistent with the accuracy of the experiments. Character of the distribution of fibrous deformations in characteristic sections of the upper belt of the truss, which perceive maximum flying and supporting moments (Figure 6,7), testifies to the efficiency and reliability of the proposed methodology for the calculation of SDS Consequently, in the metallic upper unbroken belt of the truss, which rests on elastic-pleasing wooden supports, in the process of loading, there was a regulation of SDS, which practically led to the equalization of the stresses in it estimated cross-sections, so this is an experimental confirmation of the proposed method of regulation of SDS. At that, as with a load, equal to the calculated, and higher than him, the maximum relative fibrous deformations (fibrous stresses) of the elements of the truss did not exceed calculated according to the current design norms for both metal and wooden structures and were in the boundaries of elasticity. Thus, experimentally confirmed the high efficiency of the research MWT, improved structures form with the calculated SDS regulation. In order to verify rational, in terms of material costs (values of stresses in the calculated sections of the beam of stiffness of the sprengel truss), height of the sprengel truss, the angles of the slopes of the compressed rod of the grid of the truss, the lengths of the bars of the beam of stiffness and the values of the stiffness of the reinforcement system, a numerical experiment was conducted for a combined steel sprengel truss with a span of 18 m

(Figure 8) on the "Balka" program, which was developed by the author. The structure of the combined truss (Figure 8,a) is developed and patented by the author [21-23].

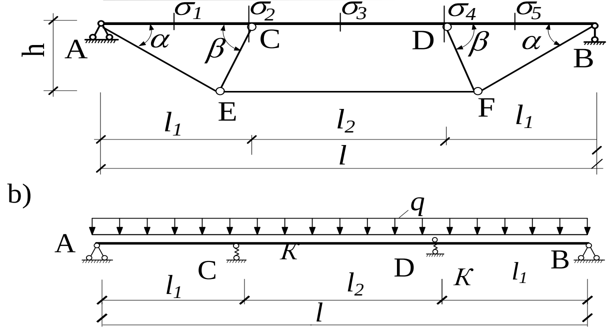

Fig. 8: a - scheme of a small-element combined steel sprengel truss with a span of 18 m; b - calculation model for a small-element sprengel truss with a span of 18 m

Numerical studies were performed in accordance with the plan of a two-factor three-level experiment [19]. According to the factors that changed the height of the sprengel truss (h = 1,5 m, h / l =1/12; h = 1,8 m; h / l = 1/10; h = 2,1 m; h / l = 1 / 8.57), slope angle of the squeezed rod of the grid of the truss (β = 30°, 45° i 60°), the lengths of the bars of the beam of stiffness (l_1 = 5m, 6m and 7m) and Ki - coefficients of stiffness of elastic supports, which simulate reinforcement system - sprengel (K = 3000 kN / m, 4000 kN / m and 5000 kN / m). When planning an experiment, the following parameters were selected:

σ_1- stress in the calculated section of the first panel of the beam of rigidity in MPa;

σ_2 - stress in the calculated cross section on the first resistance of the beams of rigidity in MPa.

Analysis of the obtained mathematical dependences, as well as their graphical interpretation allow us to determine the rational parameters of a combined steel sprengel truss with a span l = 18 m for a linear load q = 24kN / m. As a result of the processing of the plans and corresponding numerical data using the least squares method [19], the regression equation was obtained, which adequately describe the dependence of the values of stress in the calculated sections of the beam of stiffness of the sprengel truss, as criteria of a rational system in terms of material costs. Based on the obtained regression equations, isoparametric charts are constructed, which graphically describe the dependence of criteria on variables (Figure 9-12).

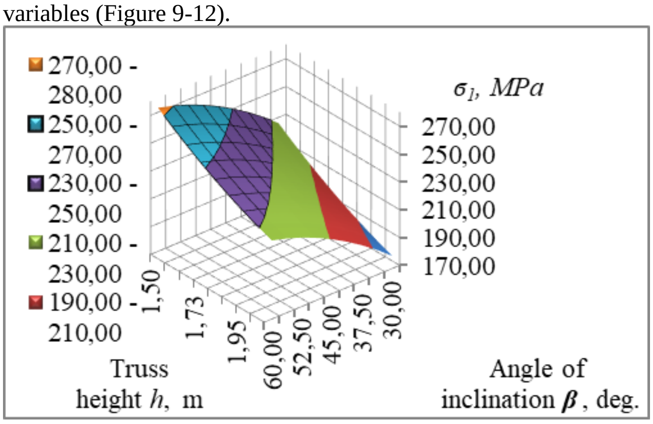

Fig. 9: Isotropometric diagram of the change in the stress values σ_1 in the calculated section of the first panel of the beam of stiffness of the sprengel truss, depending on the angle of inclination β of the compressed rods and the height of the truss h

In Figure 9, 10 shown, that the stresses σ_1 and σ_2 vary in limits from 180 to 272 MPa (for σ_1), from 142 to 241 MPa(for σ_2) when the height of the truss is changed from 2.1 to 1.5 m, respectively.

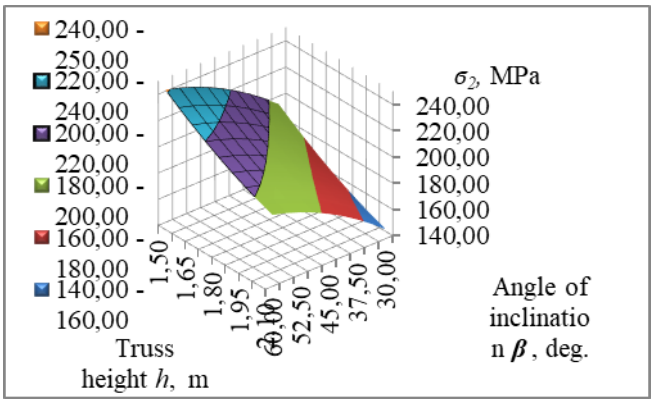

Fig. 10: Isotropometric diagram changes in the stress values σ_2 in the calculated cross section on the first support of the beam of stiffness of the sprengel truss, depending on the angle of inclination β of the compressed rods and the height of the truss h

The angle of inclination β at the same time, varies in the range from 30 to 60 °. The stresses $\sigma_1$vary from 161 to 295 MPa (Figure 11) when the coefficient of hardness K is changed from 5000 to 3000 kN / m, respectively. The length of the panel l_1, at the same time, varies between 5 and 7 m, respectively.

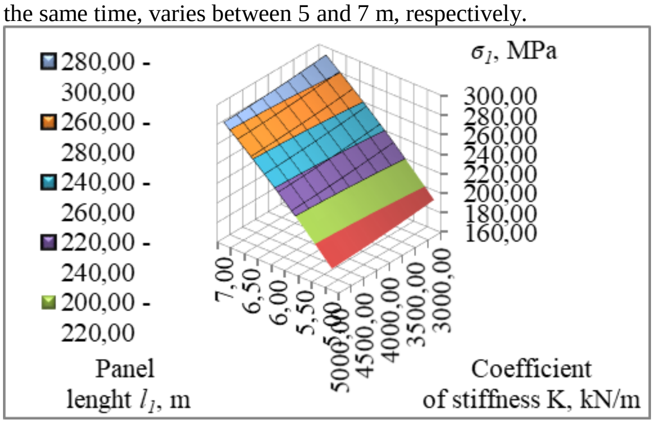

Fig. 11: Isotropometric diagram changes in the values of stress σ_1 in the calculated section of the first panel of the beam of stiffness of the sprengel truss, depending on the length of the first panel l_1 and the coefficient of stiffness to the elastic supports K that simulate the reinforcement system – Sprengel

The change in the stress σ_2 (Figure 12) has features, two maximal values of σ_2 are obtained with a panel length l1 equal to 6 m, respectively, with a coefficient of stiffness K equal to 5000, or 3000 kN / m.

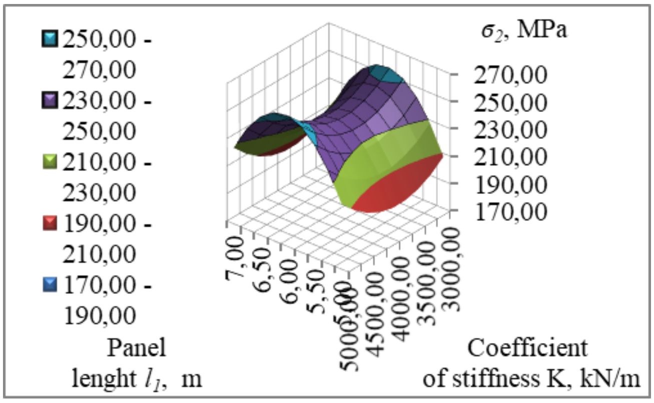

Fig. 12: Isotropometric diagram changes in the values of stress σ_2 in the calculated section on the first support of the beam of stiffness of the sprengel truss, depending on the length of the first panel l_1 and the coefficient of stiffness to the elastic supports K that simulate the reinforcement system – Sprengel

Steel savings compared to a typical 18 m span truss reaches 27% with fewer nodes and significant simplification of manufacturing technology [3]. The album was made of small-element sprengel lsteel trusses with span 12, 18, 24 and 30 m, as well as recommendations for the design of such structures [20]. Examples of implementation of such rational constructions: combined steel truss with a span of L = 18 m, concrete wares workshop "Magik Ltd.", Milatichiv village, Lviv region; small-element sprengel truss with a span L = 18 m, Truskavets city and other (Figure 13,14)

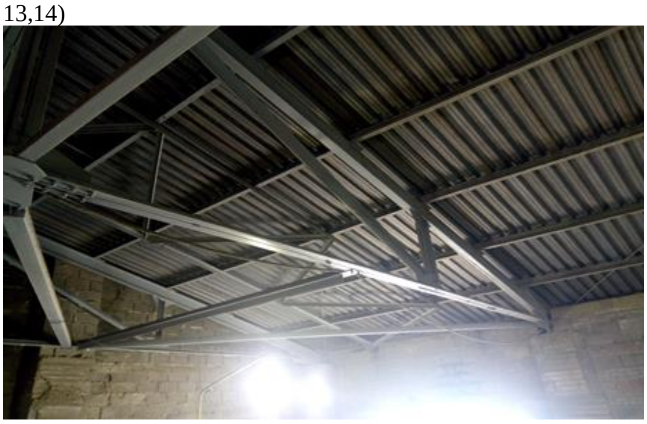

Fig.13: Combined steel truss with a span of L = 18 m. Concrete wares workshop "Magik Ltd.", Milatichiv village, Lviv region, Ukraine

Fig.14: Fragment of overlap small-element sprengel truss with a span L = 18 m, Truskavets city, Lviv region, Ukraine

Conclusions

In Analysis of the results of tests of a metal–wooden truss with a span of 12 m with the calculation regulation of their SDS allows us to make the following conclusions:

1. Results of the experiment, reflecting the real work of the metal–wooden truss are satisfactorily consistent with the theoretical ones. The crumple of wood in the knots explains a significant difference to 24.6% of the experimental deflections from the theoretical.
2. The experimentally discovered feature of MWT's work is that at the initial stages of applying external load the stresses in their elements grow almost linearly. At medium levels of external loading (0,4-0,6) from the destructive there is an intense growth of stresses in metal elements, and in the stages of loading close to the destructive there is a certain slowdown in their growth, which is explained by the completion of the process of intensive drying of wood in the nodes of joints of wooden slats and racks with metal elements.
3. Deflection of the MWT with the calculation regulation of SDS in 2.17 is less than the normative. Consequently, the high efficiency of the studied MWT is confirmed experimentally.
4. Character of the distribution of fibrous deformations in characteristic sections of the upper belt of the truss, which perceive maximum flying and supporting moments, confirmed the hypothesis about the possibility of regulating SDS on the proposed method in combined structures with elastic-supportive supports and the achievement of an stress equality state in the calculated cross-sections.
5. Identified with the help of a numerical experiment rational, in terms of material costs, height of a sprengel truss, the angles of the slopes of the crumbling rod of the truss lattice, length of the bars of the beam of stiffness and coefficients of stiffness of elastic supports

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