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STRUCTURAL EFFICIENCY OF STEEL COMBINED TRUSSES

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In this article on increasing the efficiency of steel combined structures, the tasks of rational design, regulation and control of structural parameters of elements, the use of steels with increased mechanical properties are considered. It is shown that for a six-span stiffening girder of a combined truss with elastic supports, which operates under a distributed load, the moment is 72 times smaller than the moment of a single-span beam. It is suggested to use high-strength steel for truss braces. Rationality criteria are proposed. On the basis of rationality criteria, new steel combined trusses were developed and their models were designed for stress tests. The results of experimental studies of models of combined trusses are presented. The results of experimental studies conducted on models of steel combined trusses qualitatively and quantitatively confirmed the theoretical results obtained on the basis of the proposed theory.

Keywords: combined steel truss, SSS regulation, rational design, uniform strength structure, stress-strain state, experimental and numerical studies.

Introduction

Modern trends in the development of construction acutely pose the problem of increasing the efficiency of building steel structures, reducing their material intensity based on the maximum use of all strength reserves. The demand for such economical building structures is growing all the time, which is especially relevant for Ukraine. In this regard, the development of new lightweight and at the same time reliable and durable engineering structures, primarily steel trusses, is an urgent task. It is associated with achieving the greatest economy of steel, reducing the labor intensity of manufacturing and shortening the installation time.

The desire to obtain economic structures led to the development of the concept of lightweight steel structures, which is embodied in a number of new structural forms, among which rational combined steel structures for frames of industrial, civil and agricultural buildings can be distinguished. The mass of buildings made of lightweight steel structures is five times smaller than that of reinforced concrete, metal consumption is three times lower, labor productivity is 1.5-2 times higher, and the construction period is shortened by 30-60% (Pichugin et al, 2013; Ruiz-Teran et al, 2010).

One of the methods of solving this problem is the use of stress regulation in lightweight steel combined structures in the design process, which does not require any additional material costs. The essence of such regulation consists in the rational choice of the topology of structures, the nature of fastenings on the supports, the calculation of its geometric parameters and stiffness characteristics of the rod elements. In the process of increasing the external load, there is a rational distribution of internal forces in it between the elements, with a stress-strain state similar to the effect of the prestressing (Hohol, 2018).

This, in turn, requires the development of new calculation methods and structural forms that would meet these requirements. Today, the calculation method by regulating their stress-strain state is used to a limited extent and needs further development, taking into account its approximation to practical demand.

The main advantage of combined structures is the concentration of material in the upper belt (stiffening beams), the weight of which is about 40 - 80% of the weight of the structure, as well as their low-element design. In most metal combined structures, the main (65-85%) weight of the material is concentrated in the stiffening girder, the technical and economic indicators of the whole system largely depend on the design conditions and metal consumption. The calculation of each type of such structures by the existing method has its own features. The results of such calculations give an uneven stress state along the main element - the stiffening girder, which consists in a significant difference in the support and span moments. This makes existing combined designs not always rational. Therefore, improving the calculation method of combined steel structures, which would reflect their actual state, is currently an urgent problem.

Problem statement

The main task faced by the engineer in the design of building structures is to obtain a uniformly strong structure, that is, the most rational system. Currently, the main method for obtaining such a design is the method of approximations. The number of approximations can reach a large number and depends primarily on the experience and intuition of the designer, in which the goal is rarely achieved. Therefore, the problem of calculation of building structures, including combined ones, should first of all be considered as a problem of their rational design. Therefore, rational design is an urgent problem, the solution of which will lead to a significant economic effect, and this together makes a large and important scientific problem.

In the total volume of building structures, along with others, steel ones occupy a very important place. Beam-type steel structures and trusses are the most common structural elements of floors and roofings of industrial buildings.

The creation of new rational structural forms of roofing systems, with smaller dimensions and material consumption compared to existing analogues, is an important task.

Using the calculating method of regulating the stress-strain state of steel building structures in the design process, it is possible to achieve savings of up to 27% of steel compared to typical ones, while at the same time significantly reducing the cost of the system as a whole (Bendsoe et al, 2003).

Accumulated experience in the use of rational steel structures revealed their indisputable advantages, which are particularly evident in combined structures (beam, truss, hanging and cable).

Materials and Methods

In many cases, there are several solutions to the problem, and it is necessary to choose the one that best meets the selected criteria (Gkantou, 2015).

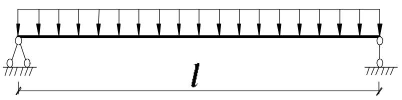
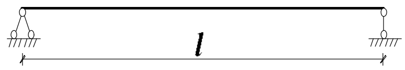
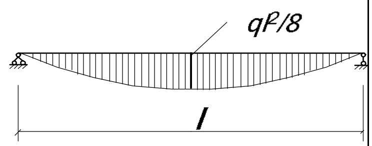
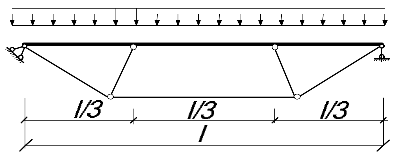
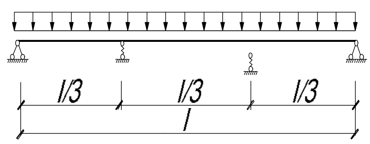
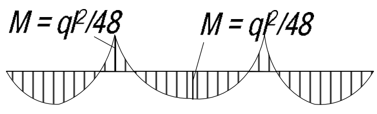
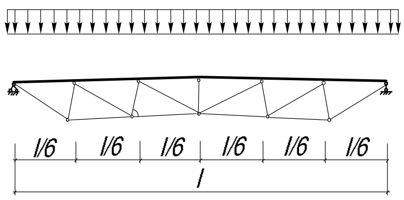
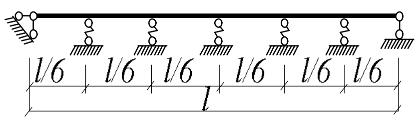
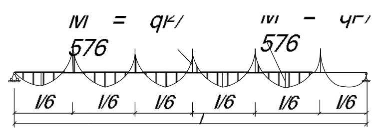
A special class of tasks for increasing the efficiency of steel combined structures consists of the tasks of rational design, regulation and control of the structural parameters of the elements. The task of designing structures is posed as a problem of rationalization of the target function - volume, weight, cost under the limitations of strength, rigidity, stability and structural requirements. The division of the task of rational design of flat rod systems under multiparametric loading, taking into account the limitations of strength, stiffness, general and local stability, and structural requirements, into two stages (after the decomposition of the system) is proposed and substantiated: at the first stage, the rational dimensions of the cross-sections of the elements at a given rigidity is searched; at the second stage, a rational ratio of rigidity is determined, using one quality criterion at each stage. This scheme allows you to use the capabilities of LIRA-CAD, MONOMS, ANSYS, ROBOT, etc. software complexes in rational design (Hohol, 2018). Rational design made it possible, along with the preservation of traditional methods of designing structures, to change the approach to solving the problem of assigning cross-section parameters. The calculation of several options with their subsequent comparison and selection of the best was replaced by methods focused on the broad capabilities of modern computer technology. The resulting rational solutions lead to a significant saving of material (up to 27%), while remaining easily feasible in practice.

Therefore, in the rational design of such structures, in order to obtain all its elements of equal strength, that is, the most rational systems, it is necessary to ensure rational geometric parameters: a rational number of supports of the stiffening girder, as well as the values of the angles of inclination of the braces and the corresponding height of the combined structure. Hence, the generalizing principle of forming new structural systems is that these systems should be combined and have as few elements and nodes connecting them as possible (DBN V.1.2-14:2018). The criterion of rationality is the energy criterion of rational design (Hohol, 2021), as well as requirements for SSS: equal tension, momentum equilibrity, maximum stiffness, or minimum weight of the structure.

Increasing the efficiency of steel combined trusses is significantly influenced by the topology of the truss itself (Lavrinenko et al, 2019). For example, by converting a uniformly loaded single-span beam, the maximum moment of which is equal to $M = ql^2/8$, into a six-span stiffness beam of a combined truss with elastic supports, which ensure the equality of support and span moments, which works for the same uniform load, we obtain the moment $M = ql^2/576$ (Table 1). This moment is 72 times less than the moment of a single-span beam, which increases the efficiency of combined systems (Ruiz-Teran et al, 2008).

Table 1

Comparison of moment graphs in beam stiffness of combined structures

Structure scheme	Calculating scheme of stiffening girder	Momentum diagram in stiffening girder
		
		
		

This conclusion is confirmed by studies (Hohol, 2021), where it was established that the potential energy of deformation and, accordingly, the weight of a beam on two supports when it is transformed into a continuous beam (stiffening girder of the truss) on intermediate elastic supports decreases intensively with a small number of spans, that is, small values of "n" (Fig. 1).

However, rational design provides only one, not necessarily the smallest value (Afshan, 2019), and the task of optimal design of steel structures is usually to find such values of selected structural parameters that provide the smallest (or largest) value of the selected criterion within the permissible design solutions.

The use of modern mathematical methods of optimization and the development of appropriate software (Fang, 2021; Farkas, 2008; Hohol, 2021) is promising for the development of effective combined structures. The theory of optimization, in contrast to variant design common in engineering practice, allows you to create a structure that will be the best in terms of material consumption with a number of systems under consideration. The creation of efficient and economic structures is also possible when optimization methods are developed and widely implemented in design practice. With a homogeneous linear elastic material, the optimal truss can be represented as a uniform-strength system. In the problem of optimal design, the volume, weight, cost of manufacture, cost of operation can be chosen as optimality criteria (Chichulina, 2020).

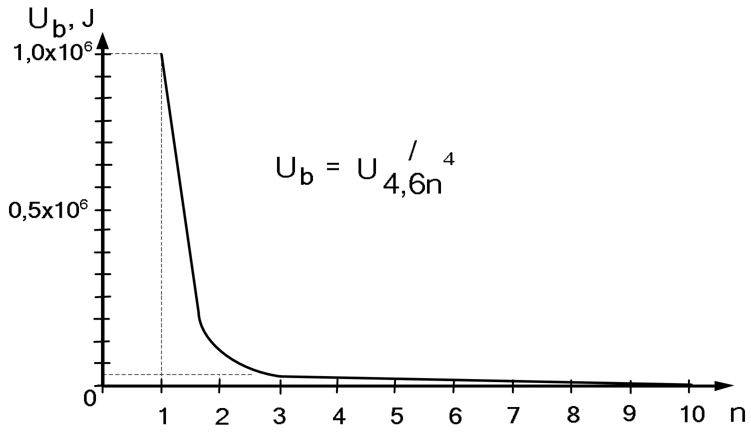


Fig. 1. Dependence of the deformation potential energy of a continuous beam U_b on the number of supports n

An important element of increasing the efficiency of steel combined trusses is the use of high-strength steels in them mentioned in EN1993-1-12. Thus, the Swedish company SSAB (Tiainen, 2013) manufactures trusses, elements of the upper and lower chords from high-strength steel - S420 (Chichulina, 2020), and bracing elements from traditional steel - S355 (Fig. 2).

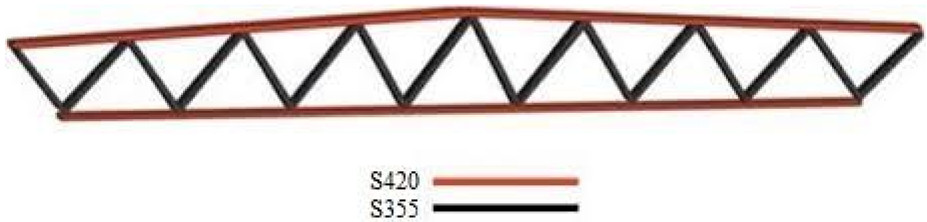


Fig. 2. Design of a roofing truss by SSAB company

According to research (Brütting, 2019), for tubular trusses with a span of 36 m at a load of 47.0 kN/m, the mass of trusses with S500 steel elements of the upper and lower belts can be reduced to 84% - 87% compared to trusses made of S355 steel and, accordingly, for S700 steel to 61% - 69%.

From this we can conclude that the hybrid construction of trusses - from different grades of steel, especially for trusses with a long span, turns out to be the most cost-effective solution. In the construction regulations of Ukraine, it is also recommended to use C345 high-strength steels instead of C255 when designing steel roofing trusses, but only in chords and supporting braces. Therefore, the use of higher grades of steel in the stretched elements of the lattice of trusses has not been studied and, accordingly, has no such recommendations, which can significantly increase the efficiency of trusses.

Therefore, creating rational constructive combined systems (for example, trusses), the criteria of rationality (efficiency) will obviously be:

- adjustment of the stress-strain state (SSS) by the calculation method;
- ensuring a uniform stress state in the calculated cross-sections of stiffness beams;
- material concentration in the main element (stiffening girder);
- low-element nature and manufacturability of structures, use of rolled steel with increased mechanical properties.

On the basis of the above criteria, new steel combined trusses were developed and their models were designed (Fig. 3) for experimental verification of theoretical provisions.

The purpose of the experimental study was to study the stress-strain state of a steel combined truss and compare it with theoretical results.

Recent studies (Hohol, 2018) of combined steel trusses have shown the prospect of development and implementation of such structures. The use of such structures allows not only to reduce material consumption, but also to simplify the process of their manufacture due to the reduction of the number of elements.

a *b*

Fig. 3. - Stress-test of steel combined truss models for asymmetric loading: a – general view; b - support node

Theoretical studies made it possible to obtain a rational topology for steel trusses and to research rational geometric parameters.

However, the research program requires verification of the obtained theoretical results. In this connection, there is a need to plan and conduct an experiment. The practical part of the study consists in testing the structural model at scale under load. This article will consider the version of stress-tests under an asymmetric load meeting DBN V.1.2.-2:2006 and DBN V.2.6-198:2014 requirments.

The model for testing is made on a scale of 1:10 from the dimensions of the truss with a span of 30 m. The span of the scale model is 3 m, and the height is 0.2 m, respectively. The topology, proportions and geometric parameters are similar to the full-size design (meeting the requirments of DSTU B B.2.6-74: 2008 and DSTU B V.2.6-10-96 standarts). Two truss models were simultaneously tested . Truss chords and racks are made of C235 class steel, stretched bracings elements are made of high-strength A400C class rods. All joints in the structure are welded. The specification of the elements is given in Tables 2, 3.

Table 2

Specification for truss "A"

№	*Element*	*Section*	*Mass, kg*
1	Stiffness beam	□40x3	10.08
2	Bottom chord	□25x3	5.82
3	Racks	□15x2	0.32
4	Racks	□20x2	0.31
5	Brace	●ø6	0.53
6	Brace	●ø8	0.95
		Total mass:	18.01

Table 3

Specification for truss "B"

№	*Element*	*Section*	*Mass, kg*
1	Stiffness beam	□40x3	10.08
2	Bottom chord	□25x3	5.94
3	Racks	□15x2	0.32
4	Racks	□20x2	0.31
5	Brace	●ø6	0.53
6	Brace	●ø8	0.95
		Total mass:	18.13

To establish the same level of both samples, a U-shaped support part is attached to the ends of the trusses.

The main support struts for samples are installed on the power floor.Samples of trusses, which have their own support part, are installed on the main risers through the support rollers.One of the rollers is welded to the top of the riser, thus simulating the operation of a fixed hinge.The other support remains free in the same way as the movable hinge.This fastening scheme simulates the operation of the beam on two supports.The trusses are located horizontally, parallel to each other at a distance of 180 mm along the axes.To ensure the stability of the structure are connected by transverse elements.With the help of U-shaped elements, a system of rods is attached over the crossed ties.The load on the units is transmitted through the rods by means of hydraulic jacks connected to the power floor (Fig.4).

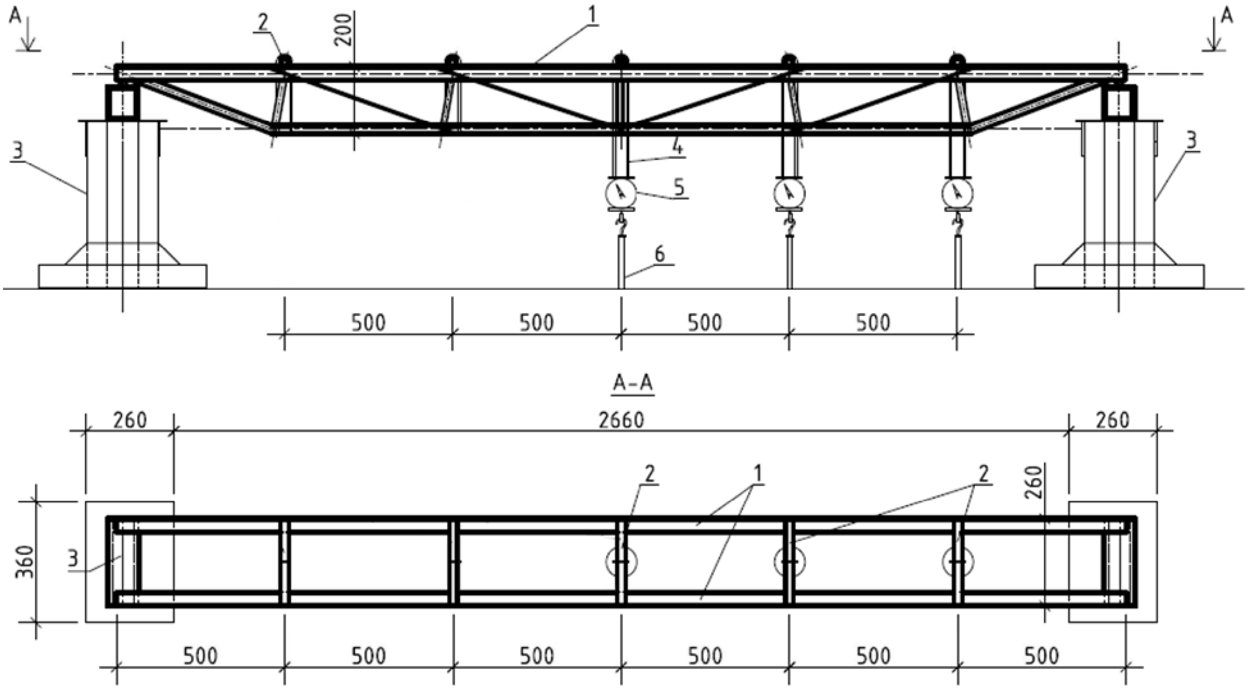


Fig. 4. Installation for steel trusses stress-test: 1 - sample; 2 - traverse; 3 - support risers; 4 - traction; 5 - dynamometer; 6 - hydraulic jack

In addition to the structural part of the installation, measuring devices are attached to the test sample. With their help, deformations in the structure are determined. The experiment program includes two methods of measuring deformations: mechanical and electrical.

Deflections of the structure are measured mechanically - vertical movements of nodes using deflection gauges. The deflection gauges are attached to the nodes on the lower belt with the help of clamping screws (Fig. 5). The accuracy of the measurement allows you to get readings of deflections up to a hundredth of a millimeter.

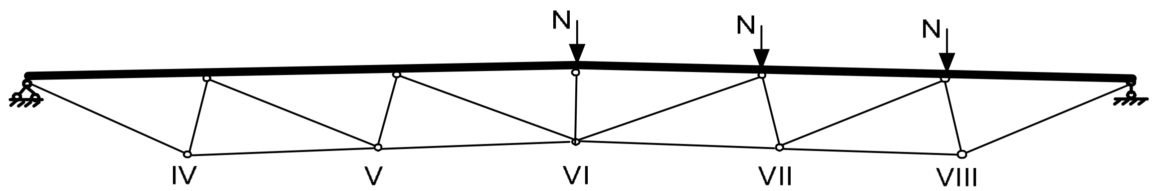


Fig. 5 Scheme of placement of deflection gauges in nodes and load application points

The electrical method of measuring deformations is called electrotensometry. Strain gauges are attached to the surface of the structure at appropriate points. Under the load, deformations occur at these points. The tensor resistor perceives the same deformations and changes its resistance value. The magnitude of the change in resistance is equivalent to the magnitude of the deformation. Another component of measurements is a device that reads readings from sensors and calculates the specific amount of deformations. In particular, it is also possible to calculate the amount of stress in the elements.

The stress-test process is divided into ten load stages, from 10% to 100% (Table 4), respectively. At each stage, the load increases by 40 kg at the node, reaching the maximum design load at the node of N=400 kg (4kN), which is equivalent to uniform distributed load q=800 ksg/m (8 kN/m).

Table 4

The value of the deflections in the nodes at each stage of loading

Stage	Load, %	N, kg	Bending, mm				
			IV	V	VI	VII	VIII
1	10	40	0,56	0,870	1,225	1,11	0,72
2	20	80	0,95	1,56	1,86	1,94	1 23
3	30	120	1,29	2,08	2,625	2,55	1,58
4	40	160	1,6	2,77	3,395	3,31	2,0
5	50	200	1,88	3,26	4,241	3,83	2,28
6	60	240	2,17	3,8	5,01	4,42	2,62
7	70	280	2,56	4,44	5,96	5,19	3,04
8	80	320	3,0	5,05	6,849	5,86	3,42
9	90	360	3,51	5,64	7,676	6,57	3,83
10	100	400	3,83	6,24	8,436	7,19	4,23

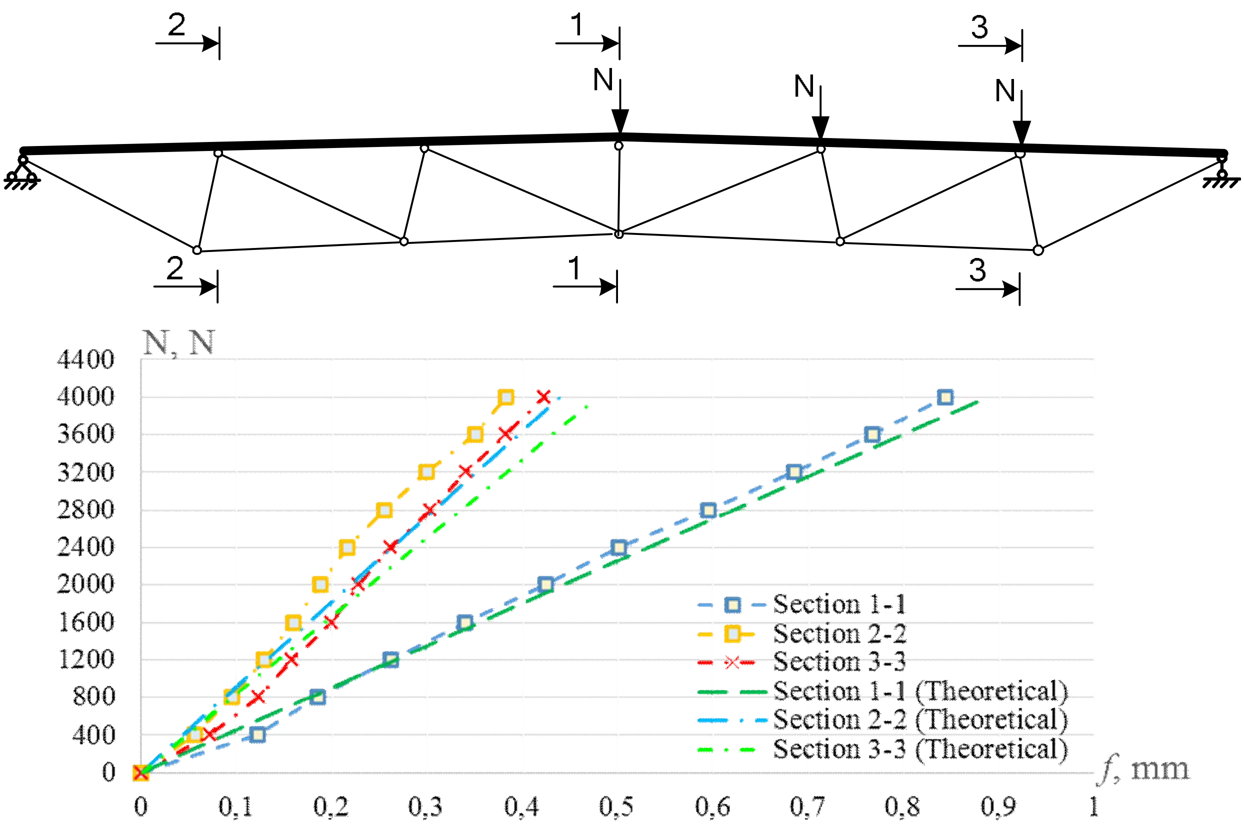


Fig. 6 Deflection graphs of the combined truss (asymmetrical load)

The load is created by a system of rods and hydraulic jacks. The magnitude of the force is controlled using a dynamometer. When the required number of divisions on the dynamometer (required amount of force on the jacks) is reached, the valve between the pumping station and the hose system is closed. Thanks to this, the pressure in the system and the force on the jacks remain constant throughout the entire test stage. After the stabilization process, instrument readings are recorded. First, readings of mechanical devices are recorded, and then readings of strain gauges. The shut-off valve is opened, additional load is supplied until the next stage of loading is reached. The algorithm of actions with each stage is repeated until reaching 100% of the calculated load q=800 kg/m (8 kN/m). After the readings of the devices at the last stage of loading are recorded, the load is completely removed from the structure. Then the readings of the devices are recorded after the load is removed. In this way, it is checked whether residual deformations are present after loading.

As can be seen from the results obtained so far (Table 4, Fig. 6), the results of the real deflections turned out to be smaller than the theoretical ones: 0.842 cm of the real deflection compared to the theoretical value of 0.888 cm. The experimental deflection of the structure is $f=l/350$, which is less than the normative value $f=l/200$. After analyzing these data, it can be concluded that the design has a certain margin of reliability. Also, analyzing the deflections of symmetrical nodes under load and without load, the difference between the deflections is 10-15%. Thus, it can be assumed that under the action of an asymmetric load, the structure works evenly, without significant jumps in deformation along the structure. The results prove the effectiveness of such structures and structural solutions in general when using combined steel trusses in cases of asymmetric loading.

The data obtained from the results of electrotensometry are shown in Fig. 7. The distribution of stresses in the stiffening girder, as the main element in which the main part (50%) of the weight of the entire truss is concentrated, is given. In comparison with the calculated (theoretical) stress values, the real data of the experiment turned out to be smaller. The maximum theoretical value was 142 MPa in the middle section under load, compared to an actual value of 125 MPa in the same section. Similarly to deflection values, stress values show the presence of a certain margin of reliability. It should also be noted that the stress values at any point do not exceed the value of 230 MPa. Accordingly, the structure works in the elastic stage without crossing the yield point.

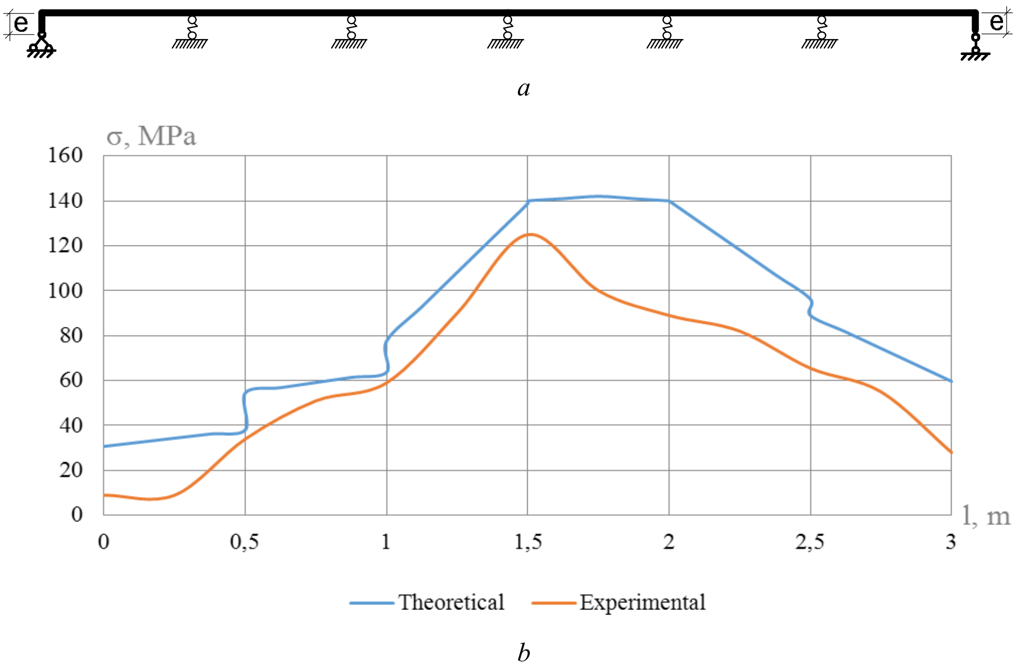


Fig. 7 Graph of stress distribution: a – calculation model of the stiffening girder, b – plot of normal stresses in the middle lines of the stiffening girder

Conclusions

The directions for further improvement of steel combined trusses through the development of rational structural forms and regulation of SSS by the calculation method at the design stage have been determined.

It was established that the problem of calculation of combined structures, first of all, should be considered as a problem of their rational design.

It is suggested to use high-strength steel for braces of the truss.

Proposed rationality (efficiency) criteria of steel combined systems.

The structural form of rational combined steel trusses has been improved.

The results of experimental studies conducted on models of steel combined trusses qualitatively and quantitatively confirmed the reliability of the theoretical results obtained on the basis of the proposed theory.

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СТРУКТУРНА ЕФЕКТИВНІСТЬ СТАЛЕВИХ КОМБІНОВАНИХ ФЕРМ

У даній статті по підвищенню ефективності сталевих комбінованих конструкцій розглянуті задачі раціонального проектування, регулювання зусиль і управління конструктивними параметрами елементів, використання сталей з підвищеними механічними властивостями. Показано, що для шести пролітної балки жорсткості комбінованої сталевої ферми з пружно-податливими опорами, які забезпечують рівність опорних і прольотних моментів, яка працює на рівномірне навантаження, момент у 72 рази менший від моменту однопролітної балки. Наведено розподіл моментів у балці жорсткості комбінованих сталевих ферм. Запропоновано використовувати високоміцну сталь для розкосів ферми. Наведено приклади застосування високоміцних сталей при виготовленні сталевих ферм із гнутих труб. Для створення раціональних конструктивних комбінованих систем (наприклад, ферм), запропоновані критерії раціональності (ефективності). Серед критеріїв раціональності зазначається енергетичний критерій, рівнонапруженість, рівномоментність, максимальна жорсткість конструкції, її мінімальна маса. На основі критеріїв раціональності розроблені нові сталеві комбіновані ферми і запроектовані їх моделі для екпериментальної перевірки теоретичних положень. Випробування проводились при несиметричному завантаженні моделей. Наведені результати експериментальних досліджень моделей комбінованих ферм. Наведено таблиці та епюри прогинів при несиметричному навантаженні. Побудовано епюру напружень у балці жорсткості. Результати експериментальних досліджень, проведених на моделях сталевих комбінованих ферм, якісно і кількісно підтвердили достовірність теоретичних результатів, отриманих на основі запропонованої теорії. Значення прогинів та напружень виявились меншими за теоретично розраховані значення, що свідчить про певну величину запасу надійності конструкції.

Ключові слова: комбінована сталева ферма, регулювання НДС, раціональне проектування, рівноміцна конструкція, напружено-деформований стан, експериментальні та числові дослідження.