Vol. 4, No. 1, 2022

https://doi.org/10.23939/jtbp2022.01.018

Dmytro Sydorak, Myron Hohol

IMPROVING THE CONSTRUCTIVE EFFICIENCY OF STEEL COMBINED TRUSSES

Lviv Polytechnic National University,
Department of Building Production
dmytro.p.sydorak@lpnu.ua

In this article, the rational constructive form of the combined steel truss with a span of 30 meters is received, with 59 % fewer elements than the typical. Calculated regulation methods are offered stress-deformation state (SDS) combined steel trusses, which make it possible to increase their efficiency. Methods of estimated SDS regulation in combined steel trusses are given: change in the stiffness of the rodsand the creation of eccentricities in the nodes connecting the lattice to the upper belt and supporting eccentricities. Designs of experimental samples of rationally combined trusses are developed. Samples of rational steel combined trusses with a span of 3 meters with SDS adjustment are developedand a reference sample of a combined rational truss. A new method of testing combined trusses using a reference sample is proposed. An experimental plant for testing combined steel trusses has been designed, which allows you to test trusses with SDS rigs simultaneously.

Key words: combined steel truss; SDS regulation; rational design; stress-deformation state; eccentricity; experimental and numerical researches.

Introduction

Current trends in construction are the acute problems of improving the efficiency of structural forms of building structures and buildings due to the development and implementation in the production of effective solutions for mass use structures. However, the design and erection of steel structures must now meet strict requirements to minimize weight and reduce construction time.

One of the methods of solving this problem is the use of combined steel trusses of square and rectangular pipes, as one of the main forms of coating structures.Due to the advantages such as reduced weight and high load-bearing capacity, combined steel rafter trusses have gained significant use in the construction of public buildings (Hohol, 2018; Pichuginetal, 2005), but need further research and development.

Analysis of existing experience in design and construction showedthat in comparison with beam and frame designs, combined systems have high efficiency (Gogol, 2015).

To increase the efficiency of steel combined trusses, in addition to rational design (Bendose et al., 2003), it is advisable to adjust the stress-deformation state (SDS) in the upper belt (stiffening beams) (Lavrinenko et al., 2019; Semko et al., 2020). The problem of their rational design first of all should be posed as a complex problem: calculation based on the method of decomposition of the system; taking into account the deformed state of the stiffening beam; SDS regulation by calculation method (Gogol et al., 2018). Rational design, which, in contrast to the optimal, does not involve the existence of any target functionality, and is expressed in the heuristic requirements for SDS structures(equal strength, equal tension, equal moments, maximum stiffness or minimum mass), which guarantees the improvement of its qualities in the most natural way. The load-bearing capacity of the structure is used to the fullest. The design having the minimum weight, manufacturability, and the minimum complexity of its manufacturing is considered rational. Thus, rational design is an urgent problem, the solution of which will lead to a significant economic effect.

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. The technical and economic indicators of the whole system largely depend on the design conditions and metal consumption. In turn, the regulation of SDS in steel combined structures in the design process does not require any additional material costs. In the process of increasing the external load in the structure is a pre-calculated rational redistribution of internal forces between the elements.

The main task in the design of building structures is to obtain a equally strong structure, ie the most rational system.

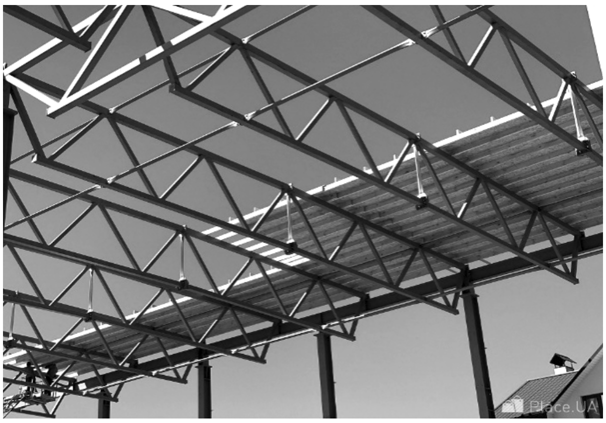
Creating structures with smaller dimensions and material consumption in comparison with existing analogues, competitive is an urgent task, which is associated with achieving the greatest savings in metal, reducing the complexity of manufacturing and reducing installation time.

The aim of the work is to develop constructive forms of combined steel trusses and experimental verification of the regulatory process.

The objectives of the study are: a) improvement of structural forms of combined steel trusses and definition of rational topology; b) analysis of the effectiveness of calculation methods of regulation; c) planning, development and preparation of experimental research.

Currently in Ukraine one of the most common are steel rafter trusses with bent welded profiles of rectangular cross section, possessing equality, with a shapeless solution of nodes (Bilyk et al., 2020; Pichugin, 2005). Such sections are convenient for designing units and attaching structures adjacent to trusses.The constructive form of such trusses belongs to the type of How (W – truss). Diagonal lattice elements are introduced to prevent each section from approaching each other. The angle of the lattice elements varies from 40 to 600, which is not always rational. The result is that long, diagonal elements work in compression, and this is not rational in terms of steel costs. The disadvantages of such trusses include the high metal and labor intensity associated with the large number of elements of the truss (Fig. 1, *a*). Design solutions with the use of such steel rafter trusses do not always allow to obtain a rational structural solution of the buildings, which provides reliability, durability and load-bearing capacity of the designed structure.

a



b

Fig. 1. Regular truss according to EN 1993-1-1:2005 (a); b – low-element truss (Hohol, 2018)

It is known that in the range of low loads, the mass of the rafters is determined not only by the actual loads, but also largely by the nature of the constructive solution mentioned in EN 1993-1-8 (Lavrinenko, 2019). This allowed to develop effective combined low-element sprung trusses with a rigid upper belt in the form of an two brandselement with a wavy corrugated wall (Fig. 1, *b*). In these trusses, the reduction of manufacturing complexity is due to the reduction of the number of lattice elements to a certain minimum, as well as the complexity of installation due to the reduction in the number of ties. Negative properties include increased sensitivity to asymmetric influences and increased deformability. This significantly limits the scope and to date they have not found mass use (Hohol, 2018; Lavrinenko, 2019).

Analysis of literature sources showed that the special literature does not sufficiently cover the problem of rational design of combined steel trusses, as well as no research on the estimated regulation of SDS, which do not give a complete picture, and the existing experience of its solution is not generalized enough (Hohol et al., 2021). All this requires improving the design of combined steel trusses, which would have fewer elements compared to typical (Hohol et al., 2020), increased rigidity compared to low-element and reduced complexity of manufacture.

Therefore, to increase the design efficiency of steel combined trusses and the advantages of the calculated method of SDS regulation, it is necessary to use: low element; the concentration of the bulk of the system in the beam; taking into account the deformed state of the stiffening beam based on the Lagrange energy variation method; exclusion of force methods; ensuring exactly the stress state of the stiffening beam only by rational selection of the stiffness of the system elements.

Materials and Methods

Trends in the development and improvement of steel structures require the design of buildings and structures with minimal reduced costs. These costs primarily include the cost of material, complexity of manufacturing and installation of structures. In order to study the increase of constructive efficiency of steel combined trusses it is necessary to choose a rational constructive form (to make a choice of rational parameters) of the considered structure, which will provide the best result according to the selected criteria.

Rational design is the basis for the formation of the technical level. The method of rational design of combined steel structures is a method of scientifically sound design, moreover, its ultimate goal can be achieved by the synthesis of rational structural forms, ensuring the rational use of strength characteristics of materials, the appropriate choice and application of new materials.

To achieve the goal of finding a rational structural form of steel combined trusses, numerical experiments were conductedand two rationalization criteria were applied – simultaneous fulfillment of the requirements of both limit states and minimization of the construction mass (Gogol, 2015; Gogol et al., 2018; Hohol et al., 2021).

Results and Discussion

Determined: the rational number of supports of the beam stiffness; height of trusses; the rational angle of the compressed rods of the combined truss and the rational ratio of the mass of the stiffening beam to the mass of the whole truss.

To find a rational number of supports of the stiffening beam on the basis of energy principles (Madrazo-Aguirre et al., 2015), a functional dependence between the deformation energy U_b during bending of a conventional (single-span) beam is obtained and the deformation energy U when bending a continuous beam of stiffness of the same length on the intermediate elastic supports and the number of its runs n (excluding the energy of the supports) (Hohol, 2018). Based on this dependence, it is concluded that, that in the case of increasing the number of beams "n" between the extreme supports of the beam, the deformation energy U_b of the beam beam on two supports during its transformation into a continuous beam by means of intermediate elastic supports decreases intensively only to the number of beams $n \le 5$, 6, that is, for a maximum of five intermediate elastic supports.

Determination of the rational height of the combined truss was carried out on the condition of the minimum area of the enclosing structures, that is, the minimum contour of the functional volume. Based on this approach, in the latest state building codes of Ukraine DSTUB B.2.6-199:2014, and adopted the maximum height of steel trusses for spans of 12–30 m from bent-welded profiles of rectangular cross-section equal to 2 m, that was accepted.

Rational angle of the compressed rods of the combined truss. The efficiency of the whole farm depends on the angle of inclination of the compressed rods of the combined truss β (Hohol et al., 2021).

Therefore, the evaluation of rational parameters of the combined steel sprung truss with a run of 30 m was performed by the method of mathematical planning of the experiment (Hohol et al., 2021).The minimum weight of the truss at the angle of inclination of the racks β equal to approximately 79–80º is obtained.

In order to determine the rational ratio of the mass of the stiffening beam to the mass of the whole truss, a numerical experiment was performed (Hohol et al., 2021).The minimum weight of truss is accepted as a criterion of rationality.The calculation of models of combined trusses was performed in the software environment "LIRA-CAD 2016 R5" for a load q = 12.75 kN/m, at a rational angle of inclination of the compressed rods of the lattice of the combined truss equal to 79º. Combined trusses were calculated at different ratios (in percent) of the mass of the stiffening beam of the combined trusses to the total mass of the trusses, equal to: 40 %; 50 %; 60 % and 70 %. It is obtained that the minimum values of the truss mass for different heights are always present at the ratio of the mass of the stiffening beam of the combined truss to the total mass of the truss equal to 50 %. On the basis of the above-mentioned rational geometrical parameters the rational constructive form of the combined steel truss with a run of 30 m is received (Fig. 2).

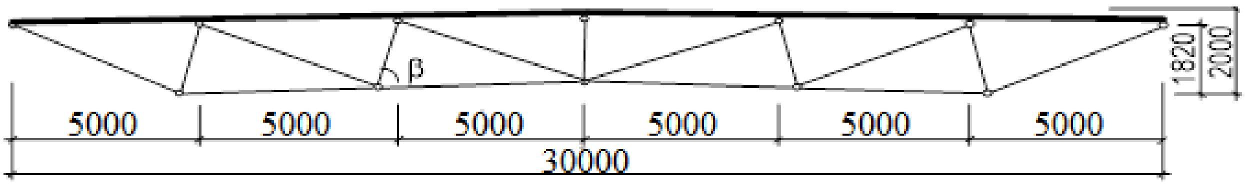


Fig. 2. Rational constructive form of the combined steel truss with a span of 30 m

With a given topology (Fig. 2) rational farm consists of six panels of the upper belt, and in the typical 10, which is 40 % more and the total number of elements of a typical truss 39 according to DSTU B B.2.6-74: 2008, and in the rational – 16, which is 59 % less.

Having obtained a rational structural form of the combined steel truss in geometric parameters, we have not yet achieved it in terms of rationality – the equality of stresses in all characteristic cross-sections in the stiffening beams.

Therefore, various calculation methods for adjusting SDS in the stiffening beam are recommended. Since SDS regulation is used to improve the quality of combined steel trusses, it can be considered a partial optimization.

The first method of estimated regulation of SDS in the beam of rigidity of a rational combined truss is the creation of reference moments on the extreme supports, what are the opposite actions from the external load (Fig. 3). Variable parameter – the value of the calculated eccentricity E to create a reference moment.

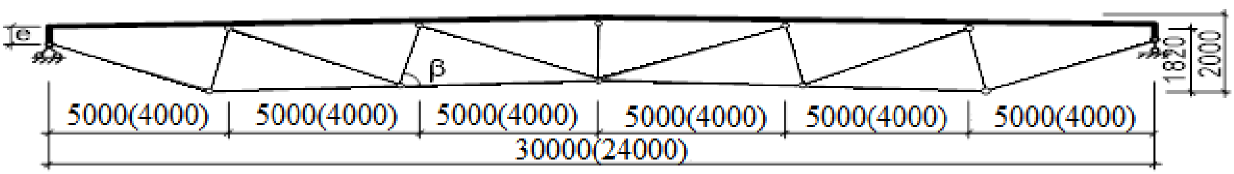


Fig. 3. Scheme for SDS regulation by reference eccentricity E

Numerical studies of this method of regulation were conducted to test the effectiveness and search for rational values of eccentricity.The results showed that for a given design, the rational eccentricity is 1.6×h – the height of the upper belt. Accordingly, this value of eccentricity was accepted for the prototype of the scale model.

The second method is to change the cross sections of the struts, struts and the lower belt A_1–A_7 (Fig. 5). Rational selection of cross sections of the middle beams, allowed to actually reduce the moments on the second intermediate support and in the central panels of the stiffening beam.

The third method is to create an eccentricity e_2–e_4 (Figs. 4, 5) in the nodes of the suspension system to the stiffening beam.Variable parameter – the values of the eccentricity e_2–e_4.

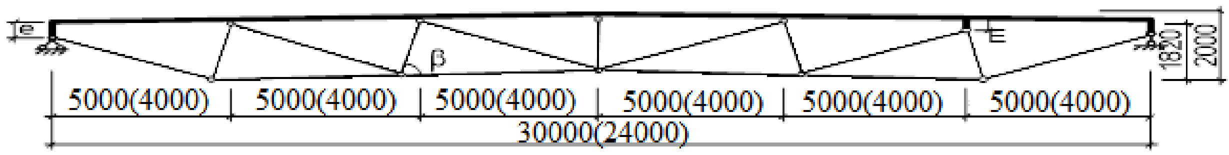


Fig. 4. Nodal eccentricity E (shown in the example of one node)

For the sake of greate rclarity, we present a rational combined truss with different methods of estimated SDS regulation (Fig. 5).

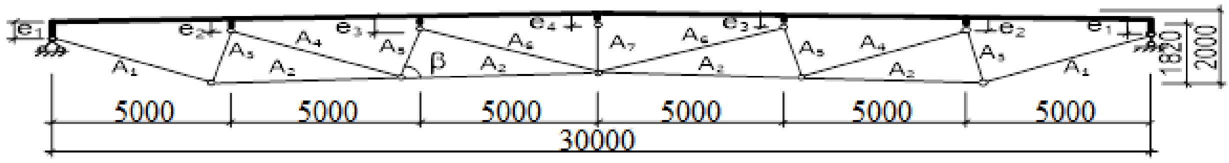


Fig. 5. General scheme of SDS regulation in the combined farm
by changing the cross sections A_1–A_7 and changing the eccentricities e_1–e_5

In practice, such eccentricities should be set symmetrically along the length of the truss. For example, we present the results of a numerical experiment of calculated SDS regulation in a 30-meter truss (plots of moments in the stiffness beam) using $e1$ = 0 and $e1$ = 1.6 h stiffness beam (Fig. 6, *a, b*). Reducing the torque from 29.7 kNm to 27.3 kNm (8 %) in the first node of the support makes it possible to reduce the cross section of the stiffening beam in the end panels.

a

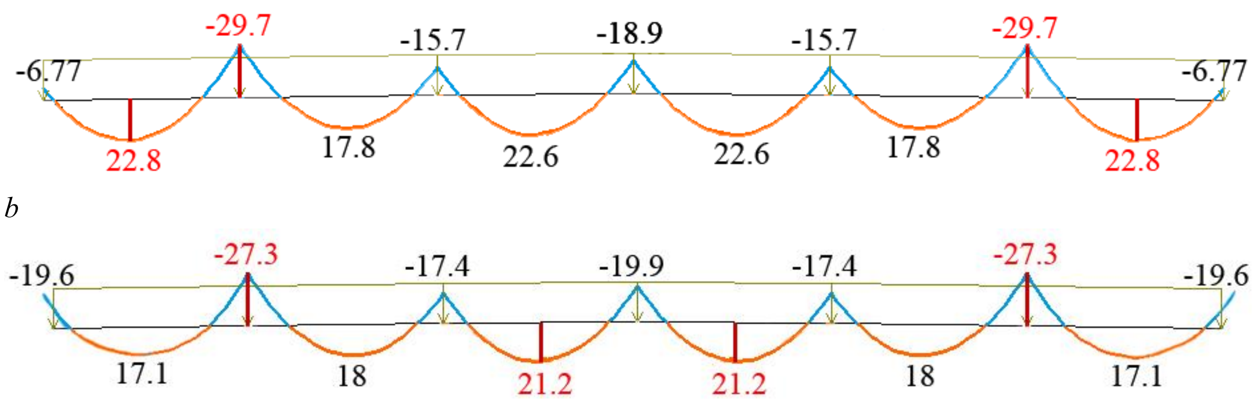


Fig. 6. Plots of moments in the beam of stiffness
of the combined truss in kNm: a – at e_1 = 0; b – at e_1 = 1.6 h beam stiffness

After investigating the parameters of the truss and selecting their rational values, designed two prototypes of steel rational trusses (Fig. 7, *a, b, c*), Table 1, 2.

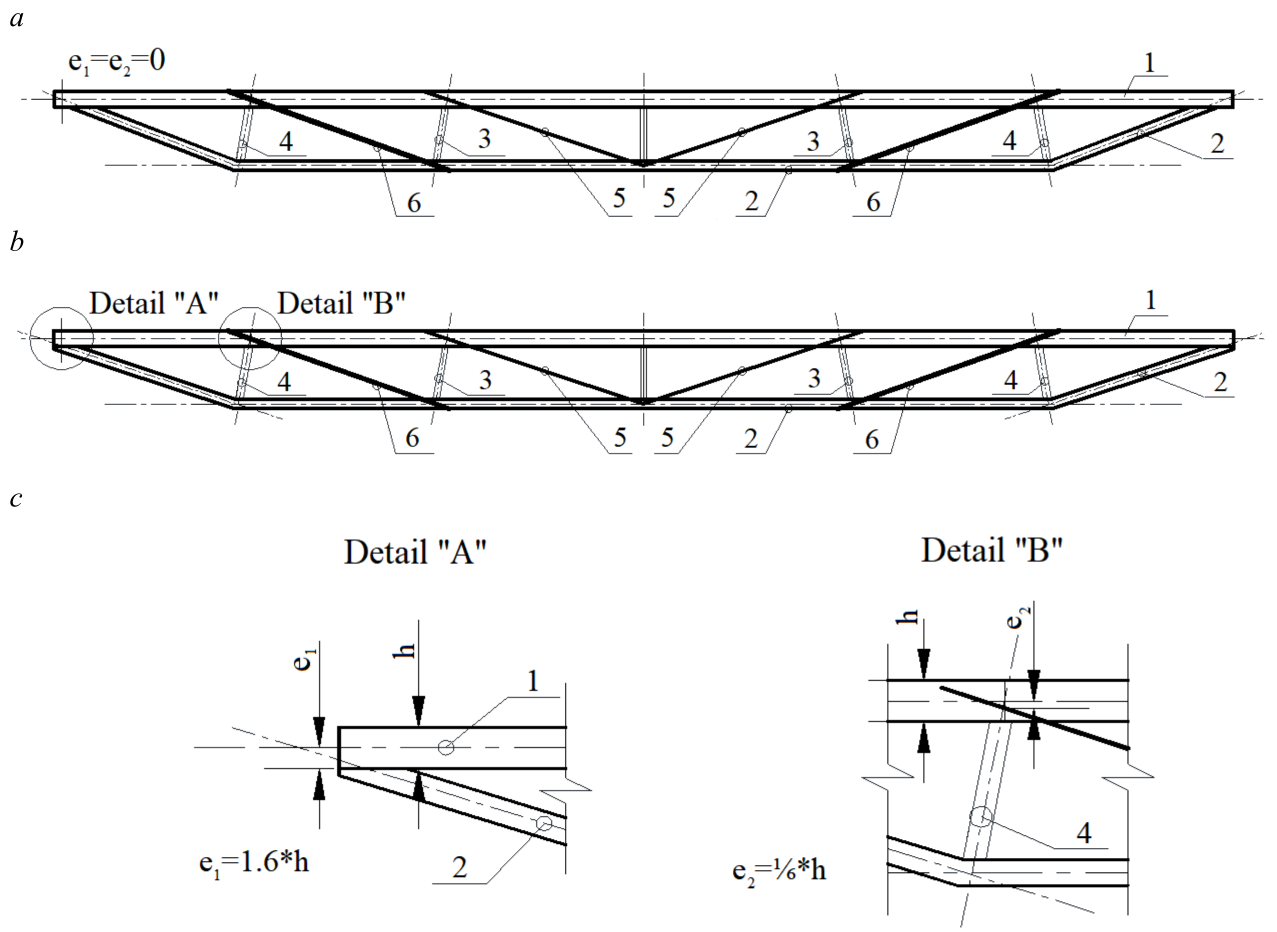


Fig. 7. Design of samples of rational combined trusses:
a – without regulation; b – with regulation of eccentricities $e_1 – e_2$; c – Details "A" and "B"

Table 1

Specification for truss "A"

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

Table 2

Specification for truss "B"

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

The first sample (Fig. 7, *a*) is designed based on the obtained rational geometric parameters without SDS adjustment.The second sample (Fig. 7, *b*) is designed similarly, but with SDS adjustment due to the applied eccentricities: reference eccentricity e_1 = 1.6×h stiffness beam;and nodal eccentricity e_2 = 1/6×h (Fig. 7, *c*).

In Fig. 8 provides photos of models of rational steel combined trusses without regulation (Fig. 8, *a, b, c*) and with SDS regulation (Fig. 8, *d, e, f*) span of 3.0 m, as well as reference (Fig. 8, *b, e*) and intermediate (Fig. 8, c, g) nodes.

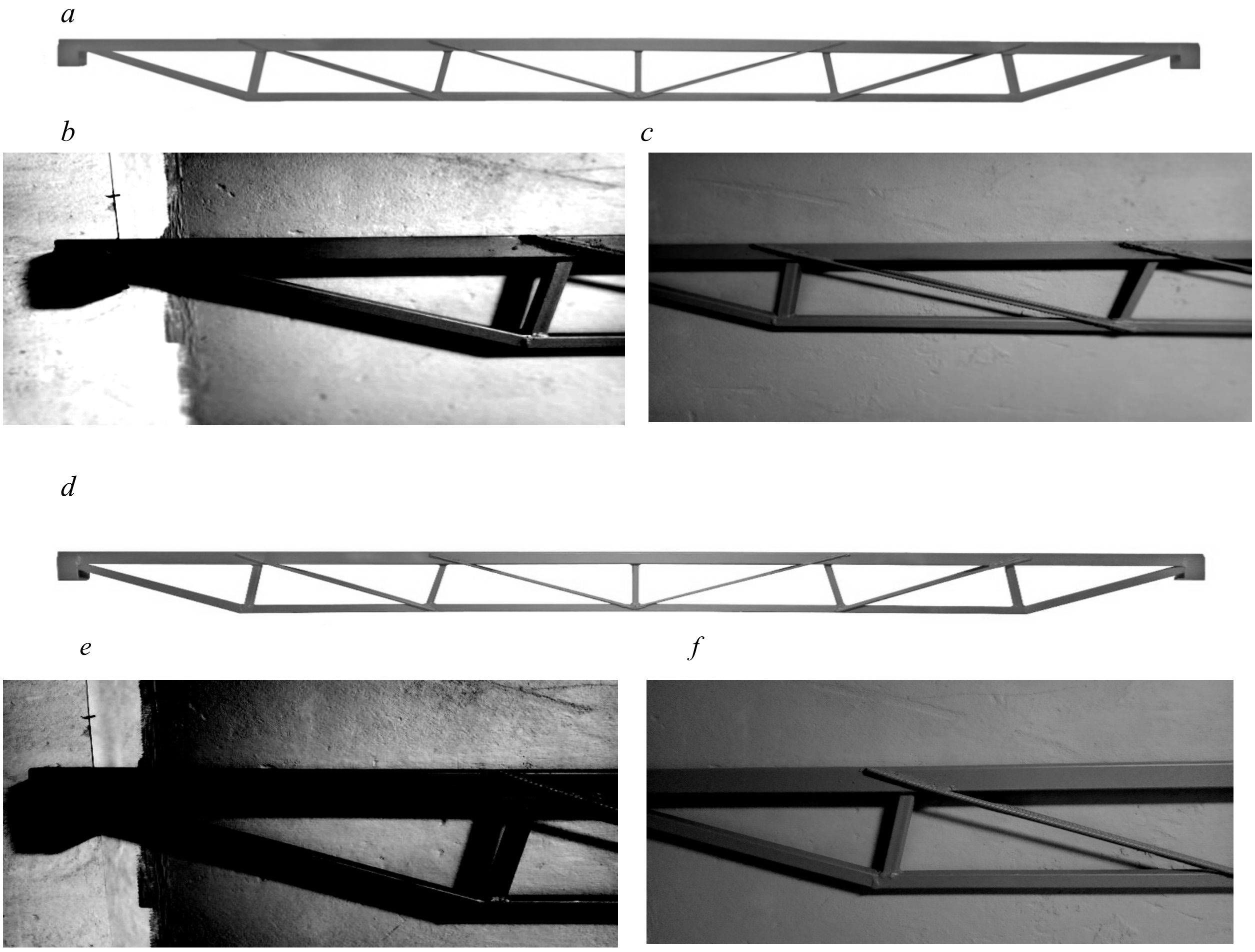


Fig. 8. Truss model with rational parameters (a); model with eccentricity in nodes (d)

For experimental testing of the given models of rational steel combined trusses with SDS adjustment with a span of 3.0 m, an experimental installation was designed (Fig. 9) referring to DSTU B B.2.6-74: 2008 andDSTU B B.2.6-10-96.

The diagram (Fig. 9) shows the main elements of the installation (Jianyangetal, 2016; Zhao et al., 2016). 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.

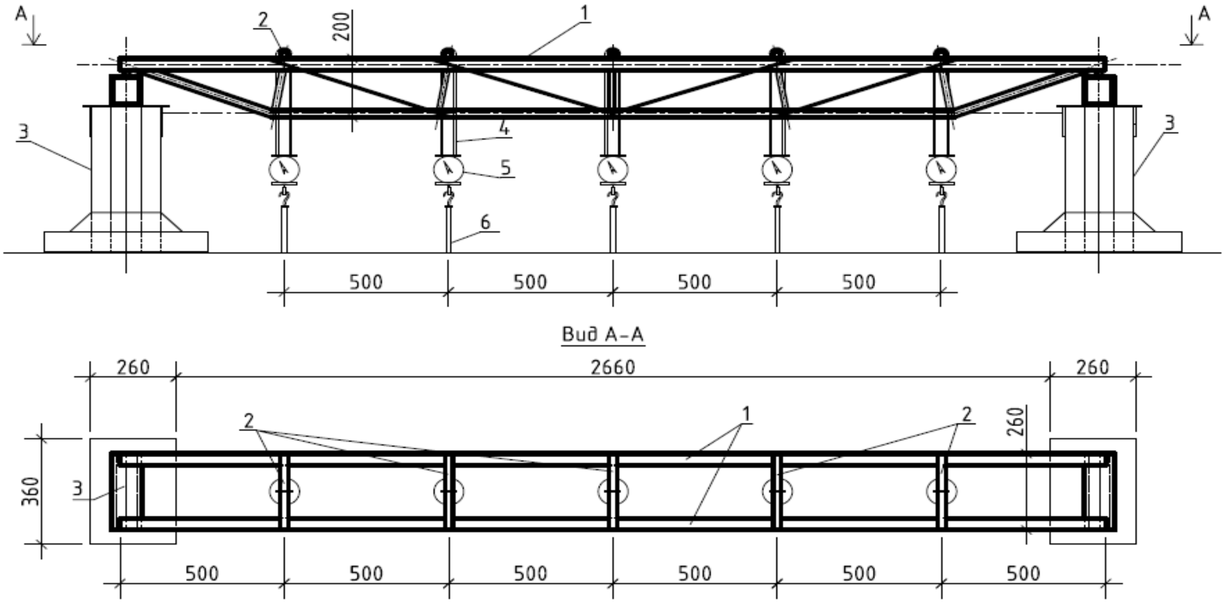


Fig. 9. Installation for testing steel trusses: 1 – sample; 2 – traverse; 3 – support risers; 4 – traction; 5 – dynamometer; 6 – hydraulic jack

The peculiarity of the tests is that at the same time, trusses with different SDS status, but with the same geometric parameters are tested on one stand: one rational truss without SDS regulation; the second with SDS regulation. This makes it possible to compare the results, ie one truss serves as a reference. All together it saves time for testing, improves the quality of work and allows for self-monitoring.

Conclusions

A rational constructive form of combined steel trusses with a span of 30 m was obtained, which has 59 % less elements compared to the typical one.

Rational parameters provide an opportunity to design a rational parametric model of a steel combined truss.

By changing the geometric scheme and purposeful regulation of domestic SDS, you can get an efficient and competitive solution of the combined truss.

Estimated methods of SDS regulation of combined steel trusses are proposed, which make it possible to increase their efficiency.

Designs of experimental samples of rational combined trusses are developed.

A new method of testing combined trusses using a reference sample is proposed.

A research facility for testing combined steel trusses has been designed, which allows testing trusses with different SDS at the same time.

References

Bilyk A. S., Tsyupin E. I. (2020). Stability of steel rods of a steel truss with rigid welded knots. *Urban planning and spatial planning*. 75, 55−71. https://doi: 10.32347 / 2076-815x.2020.75.55-7.

Bendsoe, M., Sigmund, O. (2003). Topology Optimization. Theory, Methods and Applications. Springer Verlag, Berlin Heidelberg. https://doi.org/10.1007/978-3-662-05086-6.

Madrazo-Aguirre, F., Wadee, M., Ruiz-Teran, A. (2015). Non-linear stability of under-deck cable-stayedbridge decks. *International Journal of Non-Linear Mechanics* 77, 28–40. https://dx.doi.org/10.1016/ j.ijnonlinmec. 2015.07.001.

Gogol M. (2015). The combined metal structures of the estimated regulation efforts. Czasopismoinży-nieriilądowej, środowiska i architektury. *Journal of civil engineering, environment and architecture*, JCEEA. Rzeszow, Poland. Rzeszow University of Technology, 2015.62(4/15), 107–118. https://doi: 10.7862/rb.2015.181.

Gogol, M., Zygun, A., Maksiuta, N. (2018). New effective combined steel structures. *International Journal of Engineering and Technology*, 7, 343–348. https://doi.org/10.14419/ijet.v7i3.2.14432.

Hohol, M. V. (2018). Tension regulation in steel combined structures [monograph]. Kyiv, Stal, 222 p. (in Ukrainian). https://bit.ly/3FBL97l.

Hohol, M., Kotiv, M., Kotsiy, Y., Peleshko, I., Sydorak, D., Hohol, Marco (2020). Patent of Ukraine 144193. Kyiv: State Patent Office of Ukraine. base.uipv.org/searchINV/search.php?action=viewdetails&IdClaim=271161.

Hohol M., Peleshko I., Petrenko O., Sydorak D. (2021). Analysis of calculation regulation methods in steel combined trusses. *Theory and Building Practice*, 3(1), 64–71. https://doi.org/10.23939/jtbp2021.01.064.

JianyangXue, Liangjie Qi. (2016). Experimental studies on steel frame structures of traditional-style buildings.Steel and Composite Structures 22(2):235-255. https:/doi:10.12989/scs.2016.22.2.235.

Lavrinenko L., Zotina A. (2019). Effective parameters of low-element sprung trusses with the use of I-beams with corrugated walls. *Building structures. Theory and practice*,4, 56–69. https://doi.org/10.32347/2522-4182.4.2019.56-59.

Ou Zhao; Leroy Gardner; and Ben Young. (2016). Experimental Study of Ferritic Stainless Steel Tubular Beam-Column Members Subjected to Unequal End Moments. *Journal of Structural Engineering*, 142(11). https://doi.org/10.1061/(ASCE)ST.1943-541X.0001563

Pichugin S. F., Semko O. V., Trusov G. M. (2005). Modern problems of designing steel load-bearing structures in industrial and civil construction. *Modern industrial and civil construction,* 1(1), 53–66 (in Ukrainian). https://bit.ly/3uk0LYS.

Semko O., Hasenko A., Filonenko O., Mahas N. (2020). Civil building frame-struts steel carcass optimization by efforts regulation. *Academic journal. Industrial Machine Building, Civil Engineering.* 1(54), 47–54. https://doi: 10.26906/znp.2020.54.2269.

Д. П. Сидорак, М. В. Гоголь
Національний університет “Львівська політехніка”,
кафедра будівельного виробництва

ПІДВИЩЕННЯ КОНСТРУКТИВНОЇ ЕФЕКТИВНОСТІ СТАЛЕВИХ КОМБІНОВАНИХ ФЕРМ

Одержано раціональну конструктивну форму і топологію комбінованої сталевої ферми прольотом 30 м, у якій на 59 % менша кількість елементів порівняно із типовою. Аналіз досвіду проєктування і будівництва показав, що, порівняно з балковими і рамними конструкціями, комбіновані системи характеризуються високою ефективністю. Продемонстровано, що раціональні параметри дають можливість спроєктувати раціональну параметричну модель сталевої комбінованої ферми. Запропоновано розрахункові методи регулювання напружено-деформованого стану (НДС) комбінованих сталевих ферм, які дають змогу підвищити їх ефективність. Наведено методи розрахункового регулювання НДС у комбінованих сталевих фермах: зміна жорсткості стрижнів та створення ексцентриситетів у вузлах приєднання решітки до верхнього поясу й опорних ексцентриситетів. Показано ефективність прикладення ексцентриситетів у вузлах з’єднання елементів як методу регулювання НДС. Отримані дані свідчать, що раціональні параметри дають можливість спроєктувати раціональну параметричну модель сталевої комбінованої ферми. Розроблено конструкції експериментальних зразків раціональних комбінованих ферм. Спроєктовано зразки раціональних сталевих комбінованих ферм прольотом 3 м із регулюванням НДС і еталонного зразка комбінованої раціональної ферми. Зразки виконано із труб квадратного перерізу, в яких верхній та нижній пояси нерозрізні, а з’єднання решітки із поясами шарнірне. Запропоновано новий спосіб випробування комбінованих ферм із використанням еталонного зразка і наведено його переваги. Спроєктовано дослідну установку для випробування комбінованих сталевих ферм, яка дає змогу одночасно випробовувати ферми з різними НДС. Подано схему установки, а також схеми прикладення навантаження.

Ключові слова: комбінована сталева ферма; регулювання НДС; раціональне проєктування; напружено-деформований стан; ексцентриситет; експериментальні та числові дослідження.