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IMPROVING STRUCTURAL EFFICIENCY OF STEEL COMBINED TRUSSES

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The article considers the issues of increasing the efficiency of steel combined sprengel trusses by developing rational design solutions by improving their stressed-strain state. The research methodology is based on a comparative analysis of technical and economic indicators in terms of material consumption of traditional typical and lightweight combined steel trusses. Three levels of adaptation are considered that affect the consumption of steel in the panels of the upper chord of a combined truss. Examples of achieving structure efficiency of trusses are given. A new method of practical analysis has been developed for the selection, analysis and assessment of the rationality of the stressed-strain state of stiffening girders of combined trusses. Diagrams of total normal stresses in cross-sections of the stiffening girder of a combined truss with 8 panels with a span of 30 m are given and it is shown that they are more uniform in the central part compared to a typical truss.

Keywords: combined steel truss, rational design, principles of structural efficiency, metal content, total normal stress diagram, comparative analysis.

Introduction

Scientific and technological progress in the field of construction is closely related to the problems of development and improvement of steel structures, as well as the introduction of more environmentally friendly structures - after all, the construction sector accounts for 37% of energy-related CO 2 emissions (Hamilton et al., 2020). Therefore, sustainability in construction is achieved by using materials with minimal environmental impact, maximizing the efficiency of structures, ensuring a long service life and cyclic practices. The sustainability of construction can be significantly increased by implementing structural systems that minimize the overall consumption of materials without compromising structural characteristics. In addition, the reuse of steel elements from war-torn facilities in Ukraine in the manufacture of trusses contributes to the circular economy and reduces the demand for primary materials. Such structural systems are material-efficient, resource-saving or simply structurally efficient.

In recent years, innovative approaches to steel truss design have emerged. Computational and rational design technologies have revolutionized the field of steel truss design, allowing engineers to develop highly efficient, cost-effective and cost-effective structural systems that meet the demands of the modern world and may not be apparent using traditional design methods. Advances such as parametric design, 3D modeling and digital fabrication are revolutionizing the way steel structures are designed, manufactured and constructed.

Steel construction include various combined systems that have been intensively developing recently, including steel combined trusses.

Combined trusses include structurally united: a stiffening girder - the main element, the technical and economic indicators of the entire system largely depend on its metal capacity, and the girder reinforcement system, which consists of stretched and compressed elements. The use of such structures opens up wide opportunities for creating coatings that are distinguished by lightness, high technical and economic indicators, and architectural expressiveness (Crawford, 2014; Ruiz-Teran et al., 2010; Shmukler, 2017; Tiainen et al., 2013).

Analysis of existing design and construction experience has shown that, compared with traditional truss structures, combined truss systems have a number of advantages. Achievements in the field of structural mechanics and computer technology, development and research of new structural forms, building materials, manufacturing and installation technologies have created the prerequisites for the widespread use of modern combined systems. The central place in solving this problem is occupied by the study and improvement of structural forms and methods of their calculation. They have great potential, but today they have not found mass use (Gogol et al., 2015; He et al., 2015; Hohol et al., 2022; Hohol, 2018; Hohol et al., 2021). At the same time, the scope of their application in our country is small, which is determined by a number of factors, including the lack of detailed theoretical and experimental studies of their actual operation, recommendations for design and calculation according to modern requirements, which ensure high reliability and cost-effectiveness of structures. Also, there are no in-depth studies of such systems, depending on the design features of the system.

To increase their efficiency, industrialization and competitiveness, it is necessary to ensure an appropriate, modern level of their design. This will allow designing and implementing competitive rational designs compared to analogues and the ability to create economic and technological solutions, which will lead to a significant economic effect.

Materials and Methods

The research methodology is based on a comparative analysis of technical and economic indicators in terms of material consumption of traditional - typical and lightweight combined steel trusses. The work considers steel trusses of large-span buildings with a span of 30 m. In the analysis, a truss with parallel chords, with a V-shaped lattice, also with a span of 30 m (Fig. 1), which meets the requirements of DSTU B V.2.6-74:2008, was chosen as a reference truss.

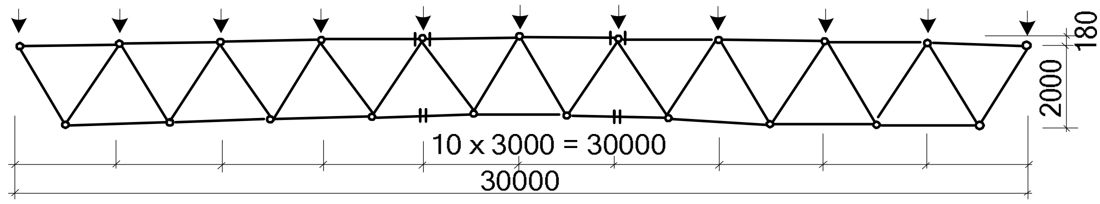


Fig. 1. Scheme of a typical truss according to DSTU B V.2.6-74:2008 with a span of 30 m

Increasing the structural efficiency of steel combined trusses is significantly influenced by the topology of the truss itself (Janušaitis et al,, 2012, Kirsch, 1989; Shymanovskiy et al., 2018), as well as its components - for example, elements of the upper chord. Achieving structural efficiency is particularly related to ensuring direct load transfer and placing material where it is needed. Highlighting the great potential of structural efficiency for minimizing metal consumption is appropriate, as it is often underestimated.

Table 1

Specification of elements for a typical truss

№	Element type	Cross section	Weight, kg
1	Upper chord	□180x140x7	1007.6
2	Support braces	□120x5	169.5
3	Lower chord	□140x7	788.2
4	Braces	□100x4	339.8
5	Braces	□100x3	85.9
		Total weight:	2391.0

Let us consider three levels of adaptation that affect steel consumption in the upper chord panel of a combined truss (Fig. 2): a- a classic beam on hinged supports; b - changing the support conditions – pinching; c - reducing the span of the panel, i.e. changing the structural system. As can be seen from Fig. 2, b, pinching both ends of the panel leads to a reduction in the span moment due to support pinching and allows saving 24% compared to a beam on hinged supports (Bendsøe et al., 1994; Weldeyesus et al., 2020).

This can be achieved by creating rigid connections or continuous multi-span beams. Reducing the span (Fig. 2, c) of a hinged beam by half reduces the bending moment for uniform loading by 3/4 and allows saving steel by 60% (Pressmair, 2023).

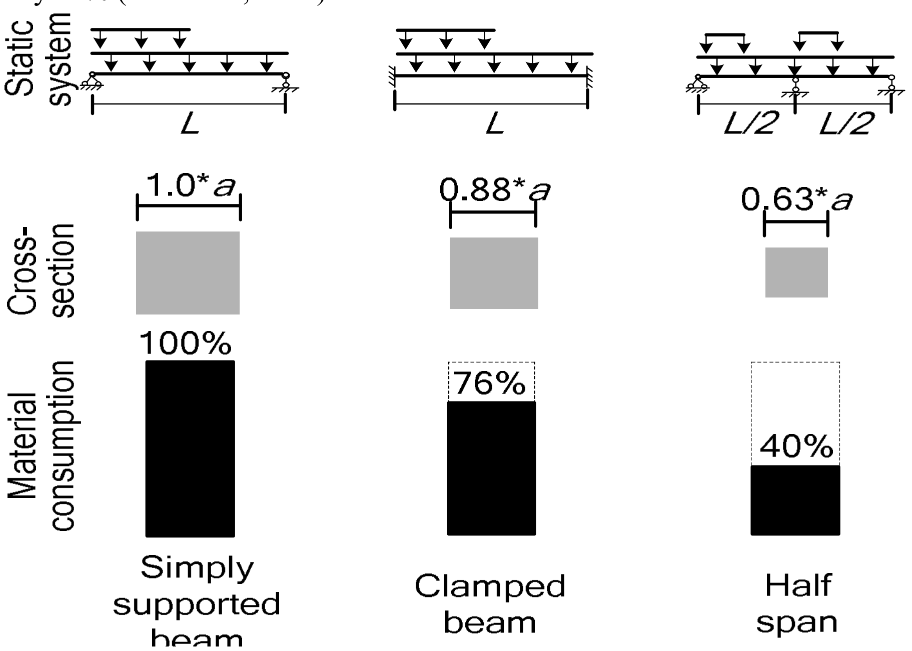


Fig. 2. Structural rationalization of the upper chord panel of a combined truss through topology optimization (adapted from (Pressmair N and Kromoser, 2023))

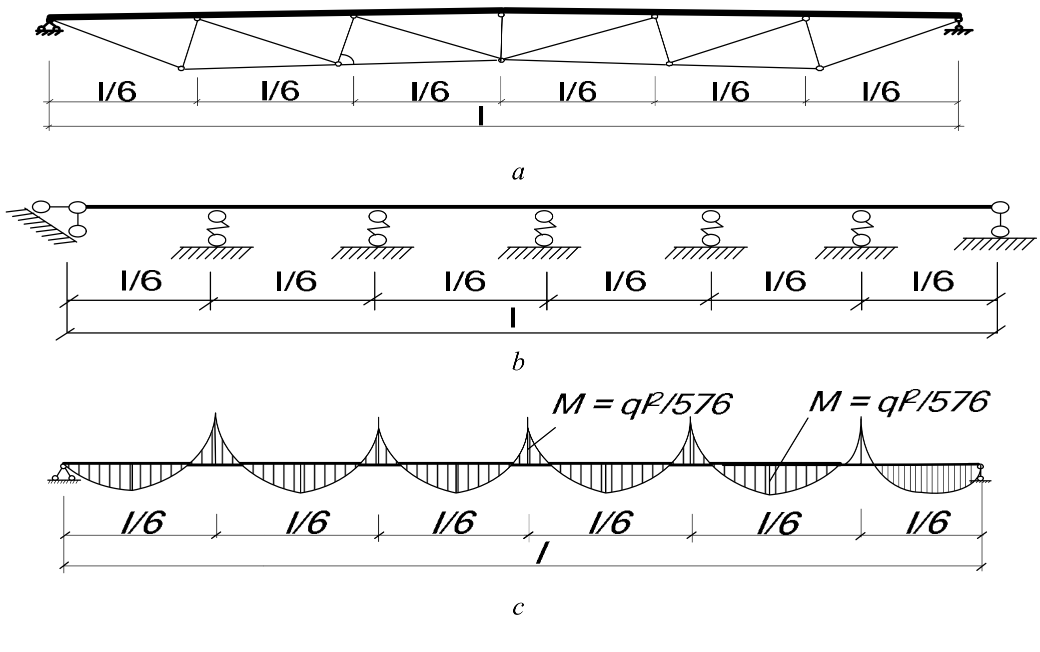


Fig. 3. a - calculated scheme of a combined truss with a span of 30 m;
b - continuous six-span stiffening girder with elastic-flexible supports;
c - diagrams of bending moments in the stiffening girder – kNm

Structural efficiency can be achieved, for example, by converting a single-span beam with a uniformly distributed load, the maximum moment in which in the middle of the span is equal to $M = ql^2/8$, into a combined truss with an indivisible six-span upper chord (stiffening girder) with elastically compliant supports (Fig. 3, b), which “conditionally” ensure the equality of the support and span moments in the panels, with a similar load, instead of the moment $M = ql^2/8$, we obtain the moment $M = ql^2/576$ (Fig. 3, c). Compared to the beam moment, it is 72 times smaller, which increases the efficiency of such combined trusses. However, such a “conditional” equalization of the span and support moments in actual real work is not ensured when taking into account deformations.

Therefore, it is simply not possible when designing such structures to ensure that all truss panels are of equal strength, that is, to achieve rational operation of the stiffening girder in combined trusses, and to use strength criteria of rationality for their design. The above does not allow designing equally stressed structures as the most rational systems. This necessitates the development of new effective methods and techniques for regulating the stress-strain state (SSS) in combined trusses.

This can be achieved using the principles of structural efficiency and practical analysis and research of the most close to effective SSS of combined trusses with an assessment of the real magnitudes of moments and normal forces, as well as changes in the normal stresses of the stiffening girder along the length of the truss.

Currently, in the field of design and calculation of building structures using personal computers, it is possible to adopt such calculation schemes that correspond to a much greater extent to the actual operation of structures and buildings. Now there is no need to simplify the calculation schemes. We propose for combined trusses (Hohol, 2018), a more accurate method, but more complicated in calculation and analysis of results, which leads to more realistic stresses, which in the calculation scheme assumes inseparability (continuity) of the upper and lower chords, and the braces and racks are connected to the chords hingedly (Fig. 4). Such a scheme ensures obtaining minimum stresses in the calculated cross-sections of the stiffening girder.

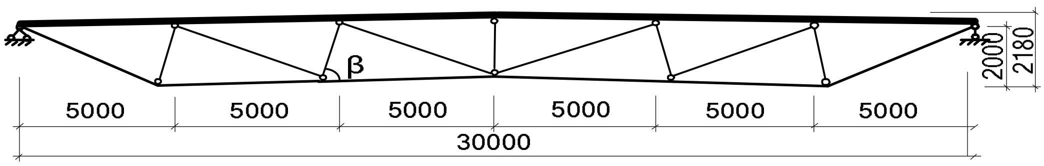


Fig. 4. Rational calculation scheme of a combined truss with a span of 30 m

So, using this rational calculation scheme, we will calculate a 30 m combined truss for a uniformly distributed load q = 18 kN/m on a PC with the program "LIRA-CAD 2016 R5" at an angle of inclination of compressed rods $\beta = 80°$. According to these results, a diagram of normal stresses σ in the cross sections of the stiffening girder was obtained (Fig. 5).

Results and discussion

For analysis of the effectiveness of proposed design solution the diagram of normal stresses, bending moments and normal forces were taken into account. Here and further in the text the term total normal stresses means the sum of stresses from bending moments and longitudinal forces in middle line of each calculated cross section of stiffening girder.

This diagram is characterized by the unevenness of the values of normal stresses along the length of the stiffening girder and their values vary from 150 MPa to 340 MPa. This leads to overconsumption of steel in the beam, that is, it is not possible to ensure rational design - equality of stresses in the design sections. All this requires the development of a new structural form of the truss, which would provide a more uniform stress diagram.

Using the principles of structural efficiency for such a design, we have proposed a combined sprengel truss with eight panels of stiffening girder and with their smaller lengths, which will make it possible to reduce the magnitude of jumps in the diagram (Fig. 6, a).

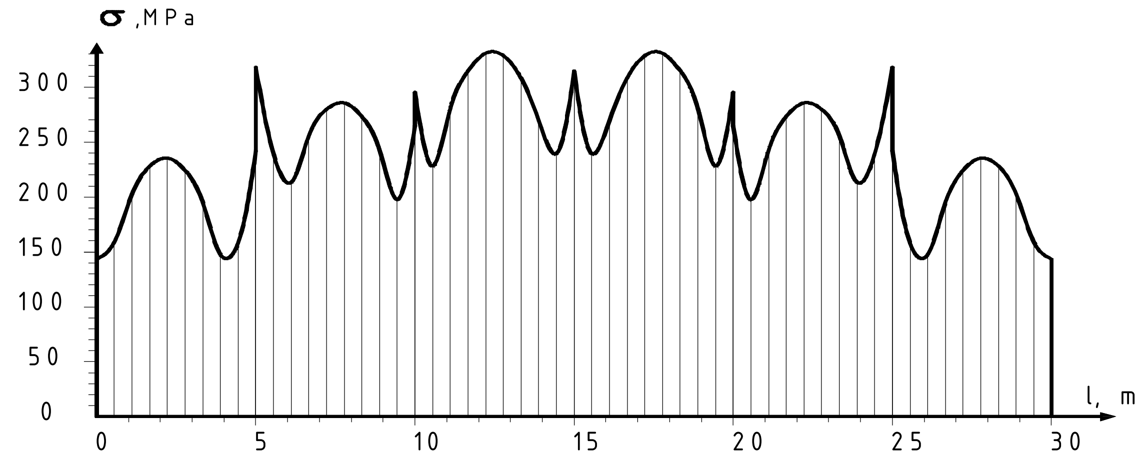
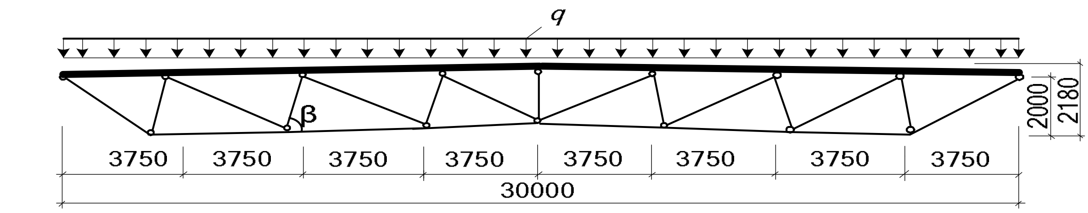
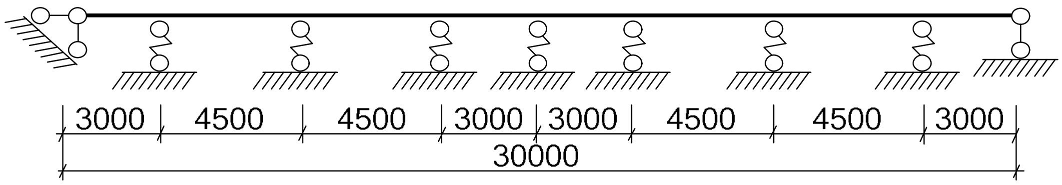


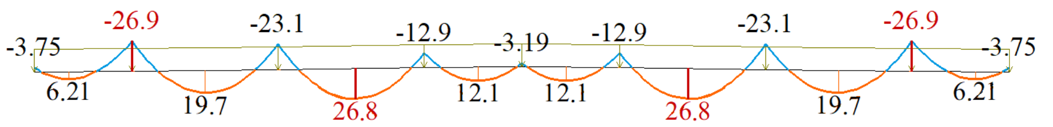
Fig. 5. Diagram of total normal stresses s in cross-sections of the stiffening girder of a combined truss with 6 panels with a span of 30 m



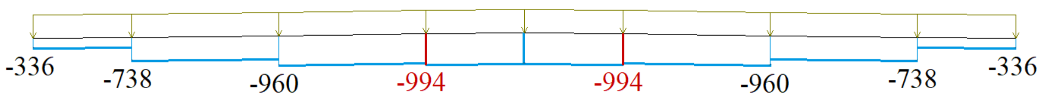
a



b



d)



c

*Fig. 6. a - design diagram of a combined truss with a span of 30 m with eight stiffener beam panels; b - continuous eight-span stiffener beam with elastically compliant supports; c - diagram of moments in the stiffener beam - kN*m; d - diagram of longitudinal forces in the stiffener beam – kN*

To select, analyze and assess the rationality of the stress-strain state of stiffening girder of combined trusses, we propose a new method of practical analysis by calculating and constructing diagrams of normal stresses from bending moments, normal forces in cross-sections of the stiffening girder of a combined truss. We will calculate a 30 m combined truss with eight panels of stiffening girder (Fig. 6, a) for a uniformly distributed load q = 18 kN/m on a PC with the program "LIRA-CAD 2016 R5" at an angle of inclination of compressed rods β = 80°. According to these results, a diagram of normal stresses s in cross-sections of the stiffening beam (Fig. 7-9) is obtained.

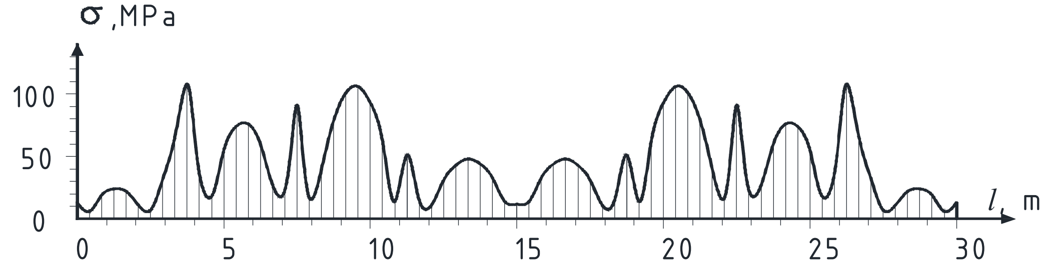


Fig. 7. Diagram of normal stresses s from bending moments M_i in cross-sections of the stiffening girder of a combined truss with 8 panels with a span of 30 m

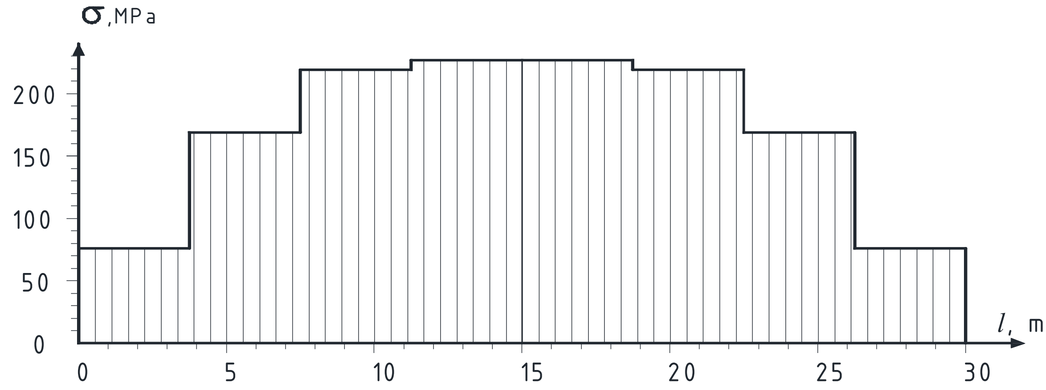


Fig. 8. Diagram of normal stresses s from normal forces N_i in cross-sections of the stiffening girder of a combined truss with 8 panels with a span of 30 m

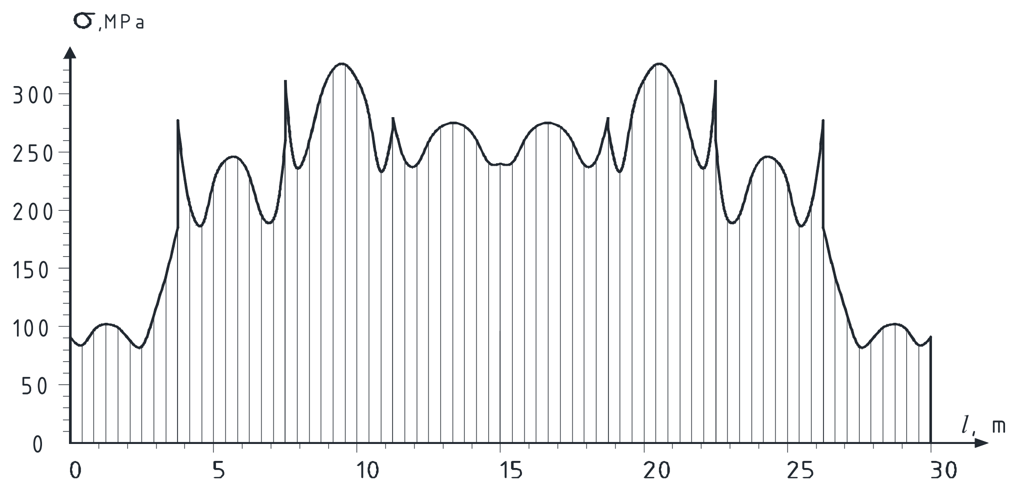


Fig. 9. Diagram of total normal stresses s in cross-sections of the stiffening girder of a combined truss with 8 panels with a span of 30 m

As can be seen from Fig. 9, the diagram of total normal stresses s in cross-sections of the stiffening girder of a combined truss with 8 panels with a span of 30 m is more uniform in the central part and the stress jumps are within the limits of 260 MPa to 330 MPa, only the supporting sections are not additionally loaded. Let us evaluate the effectiveness of such a constructive form by the mass reduction method with a typical mass according to DSTU B B.2.6-74: 2008 (Table 1, 2). As can be seen from the tables, the mass of a combined truss with 8 panels with a span of 30 m is 2099.2 kg, and the typical one mass is 2391 kg, i.e.

12.2% less. This indicates the effectiveness of the new constructive form, which significantly brings it closer to the rational stress-strain state. Therefore, the development of a new efficient structural system - combined trusses, which reduce steel consumption and consequently reduce environmental impact, are important additional steps towards achieving sustainable construction.

Table 2

Specification of elements for a combined truss with 8 panels

№	Element type	Cross section	Weight, kg
1	Upper chord	□260x130x6	1046.5
2	Lower chord	□140x5.5	707.1
3	Racks	□100x3	36.4
4	Racks	□80x3	28.8
5	Racks	□60x3	20.7
6	Racks	□50x3	8.6
7	Braces	●2ø24	251.1
		Total weight:	2099.2

The new proposed design form of steel combined sprengel trusses opens a prospective field of research for achieving more rational solution of steel trusses. Such forms allow to decrease labor intensity and material consumption which is an actual task on a way to sustainable development in field of construction. As study showed the material consumption can be reduced by 12% and labor intensity can be reduced almost twice due to smaller amount of elements and nodes.

Conclusions

Using the principles of structural efficiency creates conditions for the development of new steel combined trusses.

A new practical analysis technique has been developed for the selection, analysis, and evaluation of the rationality of the stress-strain state of stiffening girder of combined trusses.

The proposed new structural form of a combined truss with a span of 30 m provides a reduction in the mass of steel by 12.2% compared to the typical one.

The development of new efficient structural systems - combined trusses, which reduce steel consumption and environmental impact, are important additional steps towards achieving sustainable construction.

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ПОКРАЩЕННЯ СТРУКТУРНОЇ ЕФЕКТВНОСТІ КОМБІНОВАНИХ СТАЛЕВИХ ФЕРМ

У статті розглядаються питання підвищення ефективності роботи сталевихкомбінованих шпренгельних ферм шляхом розробки раціональних конструктивних рішень за рахунок удосконалення їх напружено деформованого стану. Методика дослідження базується на порівняльному аналізі техніко-економічних показників за матеріаломісткістю традиційних - типових та полегшених комбінованих сталевих ферм. Висвітлено великий потенціал конструктивної ефективності для мінімізації споживання металу. Розглянуто три рівня адаптації, що впливають на споживання сталі в панелях верхнього поясу комбінованої ферми. Наведені приклади досягнення конструктивної ефективності ферм. Показано, як використання принципів структурної ефективності створює умови для розробки нових сталевих комбінованих ферм. Розроблена нова методика практичного аналізу для вибору, аналізу і оцінки раціональності напружено-деформованого стану балок жорсткості комбінованих ферм. Проведено розорахунок різних конструктивних вирішень комбінованих сталевих ферм покриття та їх порівняльний аналіз. Наведені специфікації елементів запропонованого конструктивного вирішення комбінованих сталевих ферм, а також їх маси. Наведені діаграми сумарних нормальних напружень у поперечних перерізах балки жорсткості комбінованої ферми з 8 панелями прогоном 30 м і показано, що вони є більш рівномірними в центральній частині порівняно з типовою фермою. Запропонована нова конструктивна форма комбінованої ферми прольотом 30 м забезпечує зменшення маси сталі порівняно з типовою на 12.2 %. Показано. що розробка нової ефективної конструктивної системи - комбінованих ферм, які зменшують споживання сталі і відповідно зменшують вплив на навколишнє середовище, є важливими додатковими кроками на шляху до досягнення сталого будівництва.

Ключові слова: комбінована сталева ферма, раціональна конструкція, принципи структурної ефективності, металомісткість, діаграма сумарних нормальних напружень, порівняльний аналіз.