Structural—Parametric Synthesis of Steel Combined Trusses

Myron Hohol, Grygorii Gasii, Volodymyr Pents, and Dmytro Sydorak

Abstract The aim of the research is structural—parametric synthesis of steel combined trusses with a span of 30 m according to the criteria of minimum mass and potential energy. It is shown that the bearing capacity of the structure is used most fully when using the criterion of rational design for strength. It is shown that the largest reserves of regulation of the stress deformation state and improvement of structural forms are hidden in the combined structures. The use of combined trusses instead of traditional ones makes it possible to achieve the greatest savings in metal, reducing the complexity of manufacturing and reducing installation time. It is confirmed that the rational, technological structure of the steel combined truss with a span of 30 m, which has a minimum cost of materials, minimum labor and time for its manufacture, there will be a truss 2 m high with six panels of the upper belt. The rational, on a steel expense, angle of inclination of racks of steel combined trusses in the range 78–82° is defined.

Keywords Combined truss · Rational truss · Stress deformation state · Weight · Upper belt panel · Rational angle

1 Introduction

Improvement and development of new progressive structural forms of light steel structures of coatings in order to increase their efficiency and ensure competitiveness compared to foreign counterparts, is becoming increasingly important. These include various combined systems. Analysis of existing design and construction experience

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shows that compared to traditional beam and frame structures, combined systems have a number of advantages [5, 11, 18].

The weight of buildings can be reduced up to five times compared to reinforced concrete, metal consumption up to three times due to the use of light steel structures, increase labor productivity by 1.5–2 times, and reduce construction time by 30–60% [13]. The reduction in the weight of the combined structures, depending on the materials used, can reach up to 83% [6].

Therefore, parametric study of combined steel trusses, which will provide a rational topology and assessment of their economic efficiency is currently an urgent problem.

Of particular importance is the task of their rational calculation and design. 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 the stress deformation state (SDS) of the structure (uniformity, uniform stress, maximum rigidity, or minimum mass), which guarantees the improvement of its qualities by the most natural criterion of rational design for strength. The load-bearing capacity of the structure is used most fully.

The aim of the article is structural—parametric synthesis, topology research for design of rational (with high technical and economic indicators) steel combined trusses with a span of 30 m according to the criteria of minimum mass and potential energy, improvement of their constructive forms and comparison of efficiency in comparison with typical. The objectives of the study are: (a) determine the rational: the number of panels of the combined truss and the angle of the racks; (b) to investigate the stress deformation state of the stiffening beam with a rational topology of the combined truss.

1.1 Analysis of Basic Research and Publications

Beam-type steel structures and trusses are the most common structural elements in floors and coatings for industrial, civil and agricultural purposes. At present, the Ukrainian Research and Design Institute of Steel Structures named after V.M. Szymanowski developed a state standard for steel trusses from bent-welded profiles of rectangular cross-section [3]. This standard takes into account modern achievements in the field of steel structures, meets domestic and foreign requirements for such systems, and also provides weight restrictions, for example, the weight of the truss with a span of 30 m, for a load of 1.3 t/m should not exceed 2000 kg [3].

However, the following typical rafter trusses [3, 15] have the following disadvantages: imperfect complex topology due to a large number of elements and nodes (for example, a typical farm with a run of 30 m consists of 39 elements and has 21 nodes); incomplete use of the strength characteristics of steel in the elements along the length of the truss due to compliance with manufacturability in the manufacture; increased material and labor intensity and cost.

The problem can be solved: by developing and creating effective structural forms that meet the requirements of advanced manufacturing technologies: achieving the greatest savings in metal, reducing labor intensity and reducing installation time.

It is established that the largest reserves of SDS regulation and improvement of structural forms are hidden in combined structures [16]. Ways to increase the efficiency of combined structures are substantiated: low element, the concentration of the bulk of the system in the stiffening beam, the absence of external spacing, taking into account the deformed state of the stiffening beam based on the energy variation method of Lagrange, exclusion of power control methods, ensuring an even stress state of the stiffening beam only by rational selection of stiffness of the system elements [5].

Analysis of the development of structural forms and methods of calculation of combined steel structures shows that such structures are the most promising and they have great potential, but to date they have not found mass use [2, 5]. The use of combined structures allows to reduce steel costs to 21–27% and the cost of their manufacture, which as a result reduces their prime cost by 31% in comparison with typical designs of similar span. The main advantage of combined structures is the concentration of materials and the ability to design them low-element [1, 20].

Thus, the most promising in terms of improving the efficiency of structural forms are structures that the formation of which includes elements of beams and trusses, i.e. combined. The main load-bearing element of these structures is a stiffening beam (its weight reaches up to 70% of the total mass), from the metal content of which largely depend on the technical and economic performance of the entire system.

Currently, most attention has been paid to the study of rational combined steel trusses with a maximum span of 18–24 m [2, 21]. However, it is known that combined designs are not always rational and economical [13, 14, 17, 22–25].

The analysis of literature sources showed [5, 7] that in the special literature the problem of rational design of combined steel trusses and research of their rational topology (especially with a run of 30 m) is insufficiently covered.

Therefore, to solve this and the above problems it is necessary to investigate and develop new rational structural forms of steel combined trusses of the increased span to 30 m, which would have minimal steel costs, low labor intensity, were low-element and the most technological.

2 Presentation of the Main Research Material

We will study the replacement of traditional typical rafter steel trusses (for example, a 30 m span) combined with the same dimensions as the typical ones.

To evaluate the constructive forms it is necessary to adopt efficiency criteria. These include: volume of material; the cost of construction in the "case", or reduced value; the cost of manufacture, transport and installation. The criterion of value is of a conjunctural nature and real prices are fair at short notice. Given that the cost of steel is approximately 70% of the cost in the "case" of the structure [19], the criterion of the minimum cost should be replaced by a simpler criterion of the minimum mass of the material, which can be written as

$$M = \sum M_i = min, \; or \; M_i = \sum_{i=1}^{m} A_i l_i \rho = min, \qquad (1)$$

where M—is the mass of the structure; M_i—is the mass of the element as a component of the structure, ρ—is the density of the material.

Consider, as a standard, a typical rafter truss with bent-welded profiles of rectangular cross section with a span of 30 m and a height of 2 m with support on the upper belt (Fig. 1a) [3, 4]. It is known that the efficiency and manufacturability of trusses mainly depends on the structural shapes and dimensions [12], as well as the number of its elements [9, 10].

Let's analyze the design parameters of the following sprung trusses with a span of 30 m when working on an evenly distributed load: typical (reference)—Fig. 1a [3]; proposed combined trusses with support on the upper belt with a different number of panels of the upper belt (10 for the truss in Fig. 1b; 8 for the truss in Fig. 1c; 6 for the truss in Fig. 1d; 4 in Fig. 1e and 3 in Fig. 1f) with a lattice with descending struts and regular placement of racks, and the same angle of inclination of the racks, equal to β = 67.5°. For comparison, the overall dimensions of all trusses are the same as in the typical (Fig. 1).

The mass of each of the above trusses was determined by performing a comparative calculation on a symmetrically evenly distributed load q = 13 kN/m, with the same dimensions on the PC in the program "LIRA-CAD 2016 R5", Table 1.

From the Table 1, the mass of the trusses (Fig. 1d and g) exceeds the mass limit of 2000 kg according to [1], they are not rational for this span and load, so we will not consider them in the future. Indicators by mass of the other three truss (Fig. 1b, c, d) are less than 2000 kg and less than the mass of the reference truss (Fig. 1a).

As can be seen from Table 1, replacement of a typical (reference) truss (Fig. 1a) with a combined truss with the number of upper belt panels eight (Fig. 1c), which has a smaller number of elements (typical 39 and has 21 nodes, and combined—22 and has 16 nodes), also has a reduced mass by about 7% (Table 1). Combined truss with the number of panels of the upper belt six (Fig. 1d), compared with the combined truss (Fig. 1c), has an even smaller number of elements—16 and nodes 12, but not much more mass from the truss (Fig. 1c), by 2.5%. Thus, it is the most technological among those considered.

Also, in [5], based on the energy principles of structural mechanics, a functional dependence was obtained between the deformation energy U_b when bending a conventional beam and the deformation energy U when bending a continuous rigidity beam on intermediate elastic supports with even extremal diagram M_x, which simulates the upper belt of combined trusses, and the number of its spans n (excluding the energy of the supports):

$$U \cong \frac{U_b}{4,6n^4}., \text{ or } \lim U = \lim_{n\to\infty} \frac{U_b}{4,6n^4} = 0. \qquad (2)$$

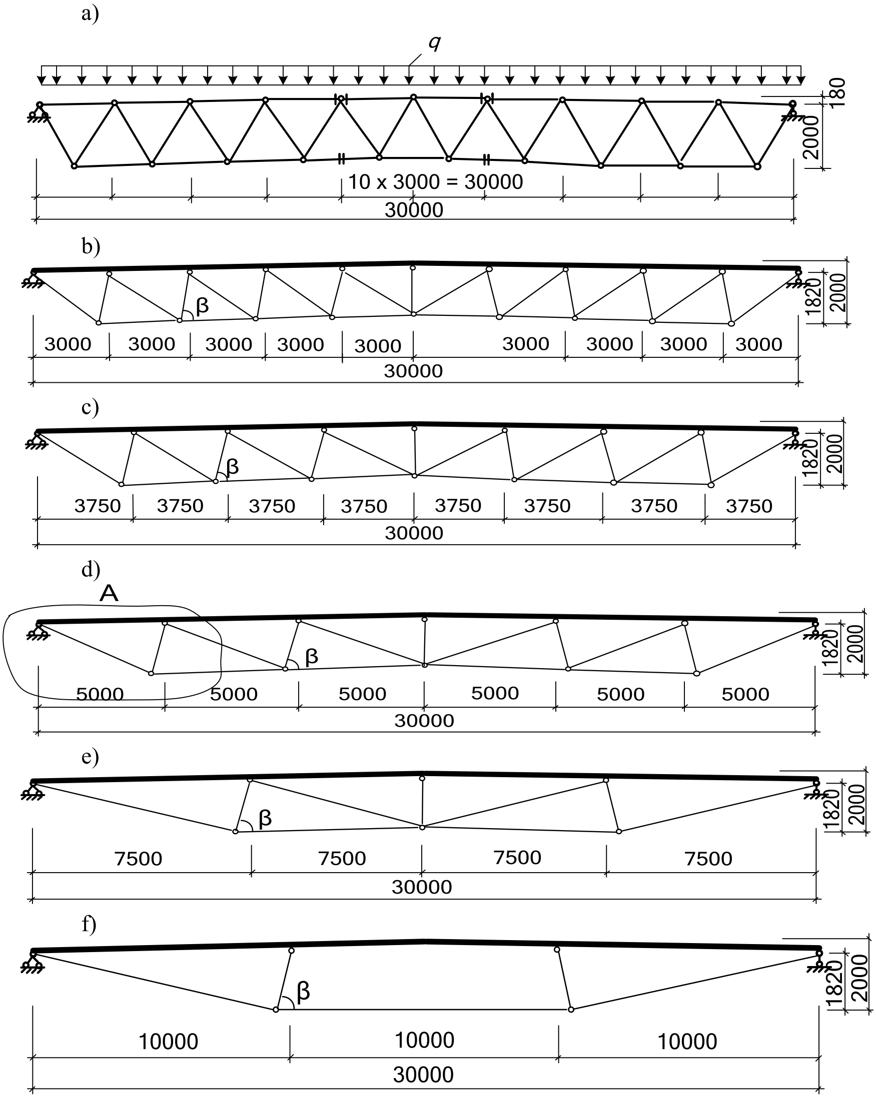

Fig. 1 Schemes of rafter steel trusses

Therefore, with the increase in the number of "n" spans of the stiffening beam (corresponding to n−1 number of its reinforcements by the struts of the sprung system) to infinity, the deformation energy of such a beam is reduced to zero, the beam turns into a rigid rod on a rigid basis in which there are no deformations of a bend (Fig. 2).

It was established [5, 8] that the mass of the beam span on two supports during its transformation into an inseparable beam on intermediate elastic supports (upper belt

Table 1 Weight and deflections of trusses

Truss	Deflection, mm	Mass, kg	Truss	Deflection, mm	Mass, kg
Figure 1a	147 mm (1/204 L)	1859,6	Figure 1d	148 mm (1/203 L)	1775,1
Figure 1b	147 mm (1/204 L)	1813,7	Figure 1e	148 mm (1/203 L)	2135.1
Figure 1c	148 mm (1/203 L)	1732,0	Figure 1f	137 mm (1/219 L)	2194.7

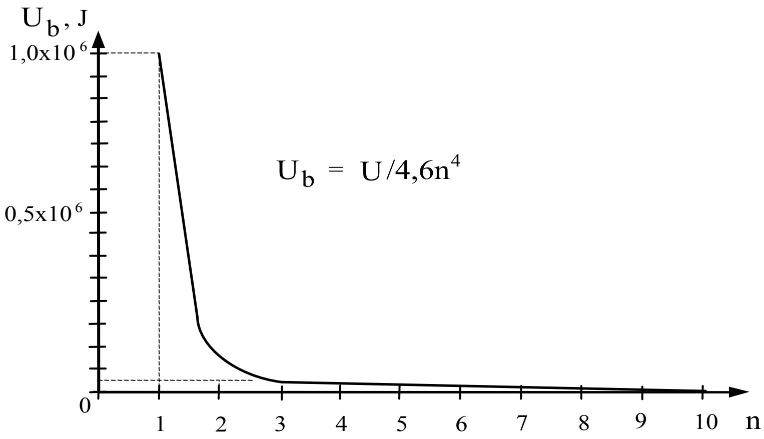

Fig. 2 Dependence of the potential energy of deformation of the beam U_b, when transformed into inseparable, on the number of its span *n* [5]

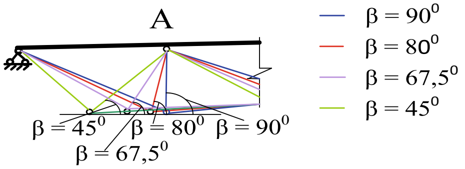

Fig. 3 Angles of the racks of the six-panel rational combined truss (node A for Fig. 1d)

of combined trusses) decreases intensively with a small number of spans, ie small values of “n” (Fig. 2).

Based on this, we can conclude that it would be rational to combine a truss with the number of panels of the upper belt six in Fig. 1d, the upper belt of which has only five intermediate supports, and the trusses in other schemes—more, have seven and nine supports. In the case of a larger number of such supports, the mass of the beam decreases slowly, while each new support increases proportionally the mass of the reinforcement system and adds to the cost of structure and increases the complexity of manufacture and installation.

Thus, such a truss (Fig. 1d) is low-element, with the concentration of the bulk of the system in the stiffening beam—the upper belt, that is, it is a rational, technological structure that has a minimum cost of materials, minimum labor and time for its manufacture.

We analyze the influence of the angle of inclination β of the racks (Fig. 1d), on the mass of a rational truss height of 2 m, with the number of panels of the upper belt—6 pieces. To do this, determine the mass of the combined trusses at different angles of the racks in the range of 45–90°: $\beta = 45°$; $\beta = 67.5°$; $\beta = 80°$; $\beta = 90°$ (Fig. 3). The calculation was performed on a symmetrically evenly distributed load $q = 13$ kN/m, on a PC in the program “LIRA-CAD 2016 R5”, Table 2.

As can be seen from Table 2 and the diagram in Fig. 4, the mass of the combined truss with the angle of inclination of the racks 80^0 is the smallest and the difference with the largest mass at an angle of 90° is 5%. The mass of the other two trusses, at angles of 67.5° and 45°, is greater than the minimum. Therefore, we can assume that the rational angle of the racks of the combined truss, the cost of steel, is approximately 78–82°, given the impact of a limited range of metal profiles and the accuracy of calculations.

Table 2 Weight and deflections of combined trusses

Truss	Deflection, mm	Mass, kg	Truss	Deflection, mm	Mass, kg
Figure 1d, Fig. 3 (angle 90°)	150 mm, (1/200 L)	1873,3	Figure 1d, Fig. 3 (angle 67,5°)	148 mm, (1/203 L)	1775,1
Figure 1d, Fig. 3 (angle 80°)	150 mm, (1/200 L)	1756,3	Figure 1d, Fig. 3 (angle 45°)	146 mm, (1/205 L)	1799.0

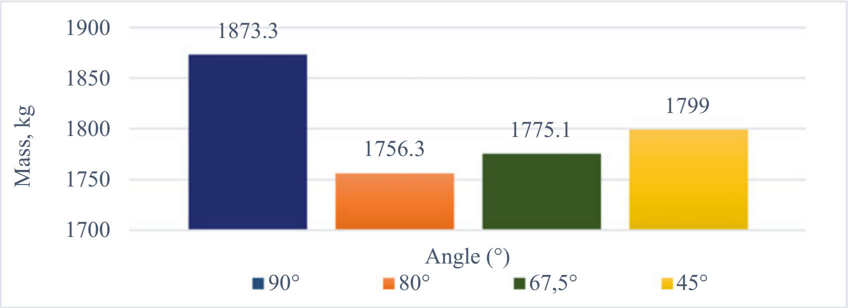

Fig. 4 Diagram of the influence of the angle of inclination of the racks β on the mass of the combined trusses

3 Conclusions and Prospects

It is shown that a rational combined steel truss with a span of 30 m has 16 elements and 12 nodes, and a typical truss of the same girder, respectively—39 elements and 21 nodes, therefore, such a combined truss should be considered low-element. Also, compared to a typical, rational combined truss has about 5% less mass, that is, it is a technological structure that has a minimum cost of materials and, accordingly, the minimum cost of labor and time for its manufacture. The combined truss with a span of 30 m and a height of 2 m will be rational, both in terms of steel costs and their energy consumption, then, when it will have no more than six panels of the upper belt, and the upper belt itself will have no more than five intermediate supports. The influence of the angle of inclination of racks of combined trusses on their mass is investigated. The rational angle of inclination of racks of steel combined trusses which makes 78–82° is defined.

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