Simulation of the stress-strain state of bi-steel beams

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One of the key challenges in contemporary construction and mechanical engineering is the development of metallic products and structures with enhanced performance characteristics while simultaneously reducing their material consumption and overall cost. A promising approach to addressing this challenge lies in the design and implementation of bi-steel structures, which rationally combine steels of different strength grades. In the present study, a comprehensive numerical analysis of the stress–strain state of bi-steel roof trusses with an 18 m span (chords made of steel S345, web members made of steel S255) was performed using the finite element method within the LIRA 10.12 software package. In addition, a comparative evaluation of their techno-economic efficiency was carried out relative to conventional mono-steel structures (steel S255). The analysis included the distribution of internal forces and load-bearing capacity in both bi-steel and mono-steel trusses. The numerical simulations confirmed that the adoption of a bi-steel configuration does not alter the fundamental structural behavior of the truss but enables a redistribution of stresses and improves overall structural reliability. Section optimization demonstrated that transitioning to the bi-steel design reduces the total truss weight by 25.1 % while maintaining its load-bearing capacity, thereby lowering transportation and on-site assembly costs. The techno-economic assessment further revealed associated reductions of 11.4 % in material costs, 16.7 % in production labor intensity, and 12.3 % in the final factory cost of the structure. The results obtained provide a foundation for further investigations, including experimental validation, studies of fatigue performance, and the development of regulatory guidelines for the application of bi-steel structures.
Key words: steel, bi-steel structures, stress–strain state, numerical modeling, material consumption, techno-economic analysis
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Introduction

The modern development of the construction industry is largely driven by the need to create load-bearing metallic structures with enhanced performance characteristics while simultaneously reducing the material consumption and overall cost of buildings. Recent studies demonstrate that varying the steel grades used in structural elements offers additional opportunities for optimizing their strength and stiffness. Numerical analyses of the stress–strain state of steels of different grades under static loading confirm that employing high-strength steels in the most heavily loaded members increases the load-bearing capacity while reducing the material intensity of the structure [1].

The effectiveness of the rational use of different steel grades is manifested not only at the level of individual elements but also in connection nodes, where appropriate material selection reduces concentrations of normal and shear stresses, improves the durability of the joint, and simultaneously decreases material usage [2]. Of particular interest are combined solutions based on the application of steels with different strength levels within a single element. Such systems, known as bi-steel structures, allow for a rational distribution of functions between materials; for example, high-strength steel may be allocated to the most highly stressed zones, while conventional-strength steel is used in regions subject to lower stress states. In effect, this approach opens new opportunities for enhancing the resource efficiency of current and future structural systems.

Over the past decades, a substantial body of international and domestic research has been devoted to studying the behavior of bi-steel elements. Experimental investigations of hybrid plates and panels [3], as well as studies of the stability of webs and flanges of I-shaped profiles [4, 5], have revealed both advantages – in terms of improved ductility and resistance to local buckling – and potential risks, such as brittle fracture under increased thickness or unfavorable loading conditions. Interest in bi-steel systems is particularly pronounced in bridge engineering and other critical infrastructure projects, where reliability and long-term service performance are of paramount importance. Analytical and numerical studies of structures combining steels of different strength grades [6–11] have shown that such solutions can perform effectively under complex loading scenarios, including eccentric compression and multi-factor loading. At the same time, reliability assessments [12, 13] emphasize the necessity of providing redundancy in bi-steel structures, since even a single failure in a highly loaded element may trigger progressive structural collapse.

The development of new structural forms of bi-steel beams that enable fuller utilization of the strength properties of applied materials constitutes an important prerequisite for creating span structures with minimal material consumption [14]. It is considered reasonable to allow the development of plastic deformations both in the web and in the extreme fibers of the lower flange of I-shaped and box-section beams. The interaction of bending moment and shear in I-beams fabricated from non-composite hybrid steel plates has been investigated under normal and elevated temperatures [15]. Based on a realistic distribution of bending and shear stresses, equations were proposed for constructing the moment–shear interaction curve without accounting for shear buckling. Substantiated arguments have been advanced in favor of using bimetallic structures as a rational design solution for viaduct-type bridge spans with straight girders [16]. Structural and analytical models have been developed that may be applied in the design of bi-steel load-bearing systems, ensuring the optimization of their parameters through the combined use of steels of different strength grades [17]. The advantages of applying composite materials in load-bearing bending components of mechanical and civil engineering structures are also highlighted, including the promising approach of reinforcing steel and bi-steel beams with composite elements, taking into account their specific deformation behavior [18].

Particular attention is devoted to issues of techno-economic evaluation of the proposed engineering solutions. Comparative calculations indicate that the transition from mono-steel to bi-steel roof trusses can reduce material consumption by up to 18 % and labor intensity of production by up to 9 % [7]. Other studies in the field of optimizing the parameters of thin-walled members and hybrid beams of stepped-variable cross-sections with constant depth [8–10, 19] demonstrate the potential to reduce material usage by as much as 25 %, while simultaneously increasing stiffness by up to 40 %. At the same time, it is noted that economic efficiency depends on multiple factors, including manufacturing technology, transportation, and assembly [20]. Nevertheless, a comprehensive techno-economic justification that accounts for the full life cycle of a bi-steel structure remains insufficiently developed.

Global experience, together with the authors' own research results, confirms that a promising structural approach for reducing the self-weight of beams, trusses, and columns is the combined use of steels of different strength grades. It should be noted that in the fabrication of such beams, the cross-sections remain constant along their length, which lowers costs compared with variable-depth members and does not complicate manufacturing, transportation, or erection. Five principal types of structural members are commonly fabricated using steels of different grades: (1) crane girders operating under service classes 1K–5K; (2) beams of bridge structures and conveyor galleries subjected to dynamic effects; (3) beams used as purlins and frame girders subjected to static loads; (4) roof trusses; (5) frame columns.

Despite active research and advances in the design and optimization of bi-steel structures, a review of recent publications reveals a number of unresolved issues hindering their widespread implementation in construction practice. A substantial proportion of the studies focus on theoretical modeling and localized experiments, while comprehensive evaluations of structures under real operating conditions – considering multifactor loading, thermal effects, and cyclic stresses – remain limited. Likewise, the set of structural solutions in which the application of bi-steel elements is expedient is not yet fully represented. Furthermore, many current design variations for bi-steel trusses, including diverse spatial layouts of their web members, ratios of steel grades, and cross-sectional types, remain insufficiently studied and require further systematic analysis. Moreover, a unified approach to the techno-economic justification of bi-steel application, one that considers the entire life cycle of the structure, has not been developed.

The purpose of the present study is to conduct a comprehensive numerical analysis of the stress–strain state of bi-steel roof trusses, followed by an assessment of the techno-economic efficiency of the proposed solutions in comparison with their mono-steel counterparts.

The object of the study is roof trusses with an 18 m span made of different steel grades, including bi-steel configurations. The subject of the study is the stress–strain state of mono-steel and bi-steel trusses under loading. The practical significance of this work lies in the fact that the results obtained provide a sound basis for selecting the parameters of bi-steel structures at the design stage, leading to substantial material savings and reduced construction costs, including in metallurgical workshops and industrial plants.

Materials and methods

A numerical study was carried out on a roof truss produced according to Series 1.460.3–23.98 "Steel structures of industrial building roofs made of closed cold-formed welded rectangular profiles with spans of 18, 24, and 30 m and a roof slope of 10 %."

The calculations incorporated the specific considerations for the use of bistable structures in roofs and floors of buildings with various functional purposes (such as industrial and public buildings), in crane runway girders, as well as in the construction of highway and railway bridges. Bi-steel beams are fabricated from steels with yield strengths ranging from 215 to 590 MPa. High-strength steels with a design resistance of R_f = 260–400 MPa are used for the flanges, whereas lower-strength steels with R_w = 210–220 MPa are used for the webs. To achieve steel savings and cost reduction, the recommended ratio of the design resistances of flange steel to web steel lies within the range of 1.4–2.0. In the calculation of the load-bearing capacity of bi-steel beams, the yield strengths of the flange and web materials are taken as equal to their design resistances R_f and R_w, respectively.

The load-bearing capacity of the trusses, in both mono-steel and bi-steel configurations, was calculated using the LIRA 10.12 software package. The steel truss under consideration has a 10 % slope and a span of 18 m (see **Fig. 1**). The truss members are fabricated from closed cold-formed welded profiles of rectangular and square cross-sections. For the mono-steel configuration, steel grade S255 was adopted. In the bi-steel configuration, the chords were made of high-strength steel grade S345, while the web members were fabricated from steel grade S255. Steel grades S255 and S345 are among the most widely used and in-demand materials in the construction industry, as they combine high strength characteristics with no significant limitations regarding weldability. The elastoplastic properties of the steels considered in the analysis are presented in **Table 1**, while their mechanical properties are given in **Table 2**.

The design schemes of the trusses, indicating the steel grade, cross-sectional profiles, and applied loads, are presented in Fig. 1.

Results and discussion

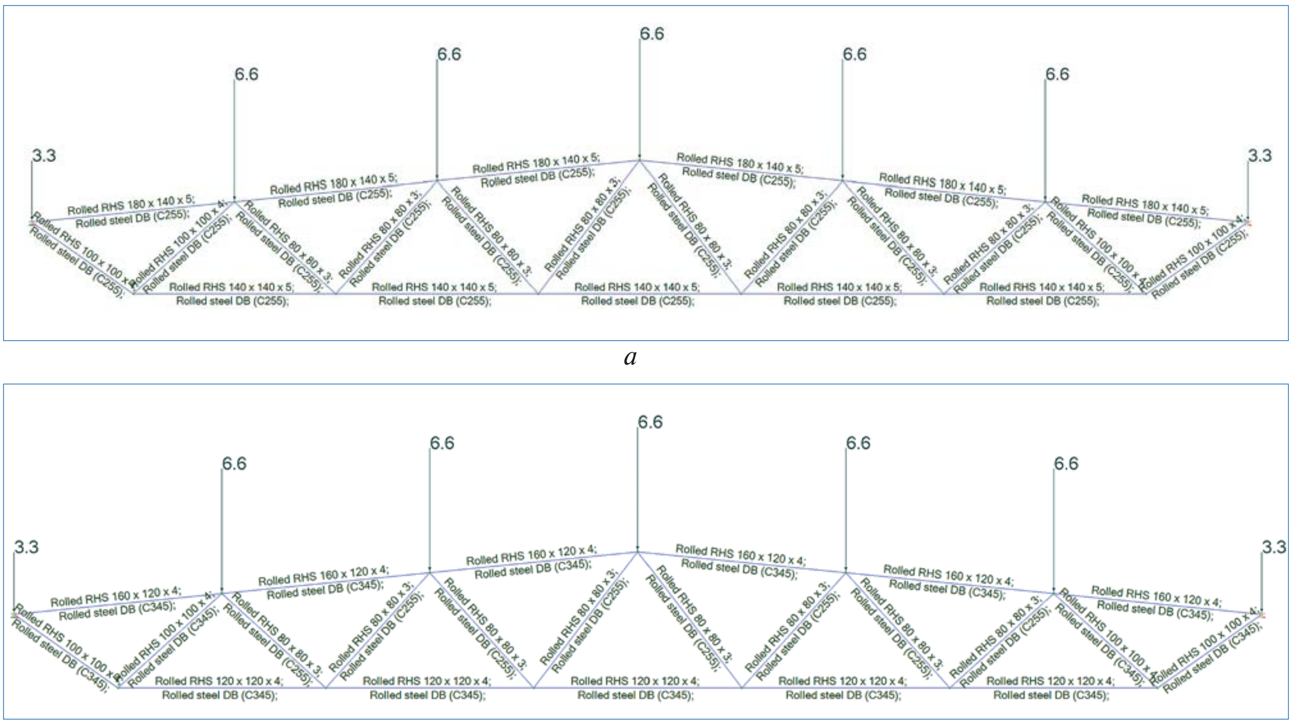
The key factor in determining the strength characteristics of bi-steel beams is the spatial distribution of materials with varying levels of mechanical properties within the cross-section. The structural scheme, which dictates the placement of high-strength steel relative to zones of maximum tensile and

Table 1. Elastoplastic properties of the considered steel grades

Designation	Standard	Steel grade	Elastic modulus, MPa·10^5	Shear modulus, MPa·10^5
S255	GOST 380-2005	St3Gps, St3Gsp	2.06	0.78
S345		09G2S, 12G2S		

Table 2. Mechanical properties of the considered steel grades

Designation	Standard	Steel grade	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, %
S255	GOST 380-2005	St3Gps, St3Gsp	255	380	20
S345		09G2S, 12G2S	345	490	15



b

Fig. 1. Design schemes of the trusses in different configurations: *a* — mono-steel variant (steel S255); *b* — bi-steel variant (steels S255 + S345)

compressive stresses, largely governs both the overall stiffness of the element and the pattern of internal force redistribution under increasing load. Furthermore, local stress concentrations arising in the transition zones between dissimilar materials significantly impact the structure's durability and define the beam's ultimate limit state. Consequently, justifying the selection of the steel combination scheme within the cross-section is an essential preliminary step, enabling the correct interpretation of subsequent computational results and comparative analyses.

In engineering design practice, the cross-sections of bi-steel beams may take the form of an I-section or a closed box profile and can be classified as either symmetric or asymmetric. The choice of a specific configuration depends on the structural service conditions, the distribution of internal forces, and the stiffness requirements. Of particular importance is the rational use of high-strength and ultra-high-strength steels. Depending on the design scheme, the magnitude of bending moments and shear forces, as well as the degree of asymmetry of the cross-section, it may be feasible to use ultra-high-strength steel in only one flange of the beam or in both flanges simultaneously. This approach allows for targeted enhancement of the load-bearing capacity of the most highly stressed elements while simultaneously optimizing material usage and reducing the overall mass of the structure, which is especially critical in the construction of major span structures and other large-scale engineering facilities (see **Fig. 2**).

Symmetric or nearly symmetric cross-sections (with a small degree of asymmetry), in which both flanges are made of high-strength steel, are recommended in cases where

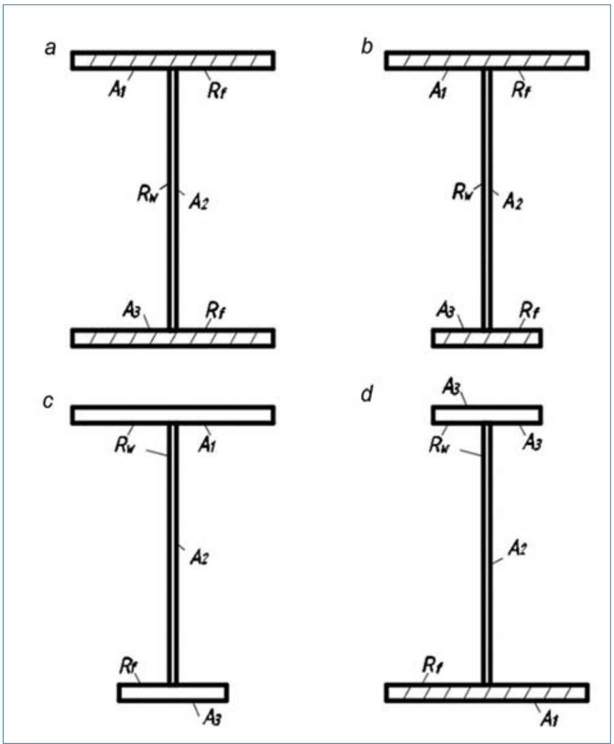


Fig. 2. Variants of bi-steel beam configurations:
R_w and A_w – design resistance and area of the web;
R_f and A_f – design resistance and area of the flanges

the primary structural actions are bending moments acting in one or two mutually perpendicular planes (Fig. 2, *a* and *b*). This configuration ensures a uniform distribution of stresses between the top and bottom flanges, enhances the overall stiffness and stability of the section, and minimizes the likelihood of local buckling of the elements. In contrast, for pronounced uniaxial bending combined with significant cross-sectional asymmetry, it is rational to use a design in which only one flange (the smaller one in geometric dimensions) is made of higher-strength steel (Fig. 2, *c*). This approach allows targeted compensation for the imbalance in the performance of the flanges while preserving the savings of costly high-strength steel. Under uniaxial bending conditions, the preferred solution is a cross-section in which the larger flange, carrying the majority of the bending moment, is fabricated from higher-strength steel (Fig. 2, *d*). This structural scheme provides a rational distribution of load-bearing capacity, improves the beam's performance under combined bending and compression, and in many cases proves to be the most efficient solution in terms of strength and material efficiency.

The selection of the optimal cross-section involves determining the geometric dimensions of the web (height and thickness) and the flanges (width and thickness). In general, the beam height h is determined by the allowable deflection, material strength, and techno-economic requirements. The minimum permissible height is established based on the requirements of the second group of ultimate limit states, while the maximum height is governed by techno-economic considerations. The web thickness tf is determined as a function of the overall beam height according to the relation $t_f = (1/200 \div 1/250)\cdot h$, with a typical minimum of 6–8 mm. The flange width b_w is taken as $(1/2 \div 1/5)\cdot h$, and the flange thickness t_w is typically $(2–3)\cdot t_f$.

It is generally assumed that the bi-steel beam operates in the elastoplastic stage, as plastic deformations may develop in the portions of the web adjacent to the flanges when stresses reach the design resistance in the ultimate state. Traditionally, the development of plastic deformations in bi-steel beams during strength calculations is accounted for in two ways: (a) plastic deformations are considered only in the webs; (b) limited plastic deformations are considered in both webs and flanges.

The mosaics of the resulting internal forces in the truss members are shown in **Fig. 3**. In both models, the pattern of axial force distribution is qualitatively similar. The maximum tensile forces are concentrated in the lower flange (approximately 47 tf), while the maximum compressive forces occur in the upper flange (approximately –46 tf), which is generally consistent with the behavior of symmetric diagonal trusses under uniformly distributed loading. In the bi-steel truss, high-strength steel is assigned to the most highly stressed members, allowing for a redistribution of stresses and a reduction in the risk of elements exceeding the elastic limit. As a result, the load-bearing capacity of the bi-steel truss is higher at the same material consumption, and sectional optimization can further reduce the overall structural mass. Effectively, the use of bi-steel does not alter the fundamental

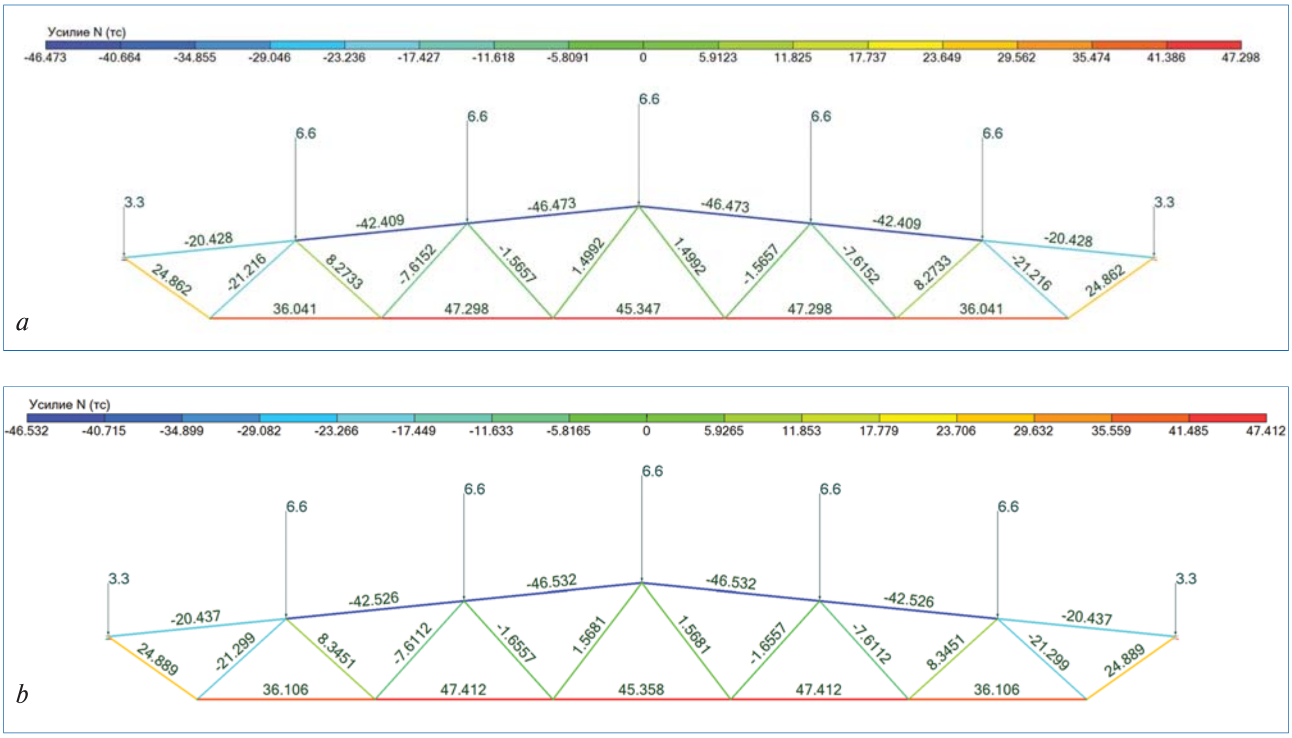


Fig. 3. Mosaics of axial forces in the trusses: *a* — mono-steel (steel S255); *b* — bi-steel (steels S255 + S345)

force pattern of the truss, but it significantly enhances operational reliability and economic efficiency. That is, by differentiating the steel according to the load-bearing role of the elements, the more expensive high-strength steel is used only where it is truly required, as indicated by the modeling results.

The verification of the load-bearing capacity of the truss members, indicating the combined utilization percentages for the first group (strength, overall and local stability) and the second group of ultimate limit states (slenderness and deflections), is shown in **Fig. 4**.

The results of the calculations for the mono-steel truss with optimized cross-sections are presented in **Table 3**, and for the bi-steel truss in **Table 4**.

The substantial savings in steel demonstrate the high resource-efficiency potential of bi-steel structures, fully aligning with contemporary trends toward reducing material consumption in construction.

To justify the techno-economic feasibility of using bi-steel structures, a cost analysis was performed for the fabrication of roof trusses made of steel grades S255 and S345 in both mono-steel and bi-steel configurations. The calculation methodology was based on standard relations for determining the cost of primary materials, manufacturing labor, and the final factory price of the structure [7]. The cost of the materials used to fabricate the truss was determined taking into account the wholesale price of the set of rolled profiles,

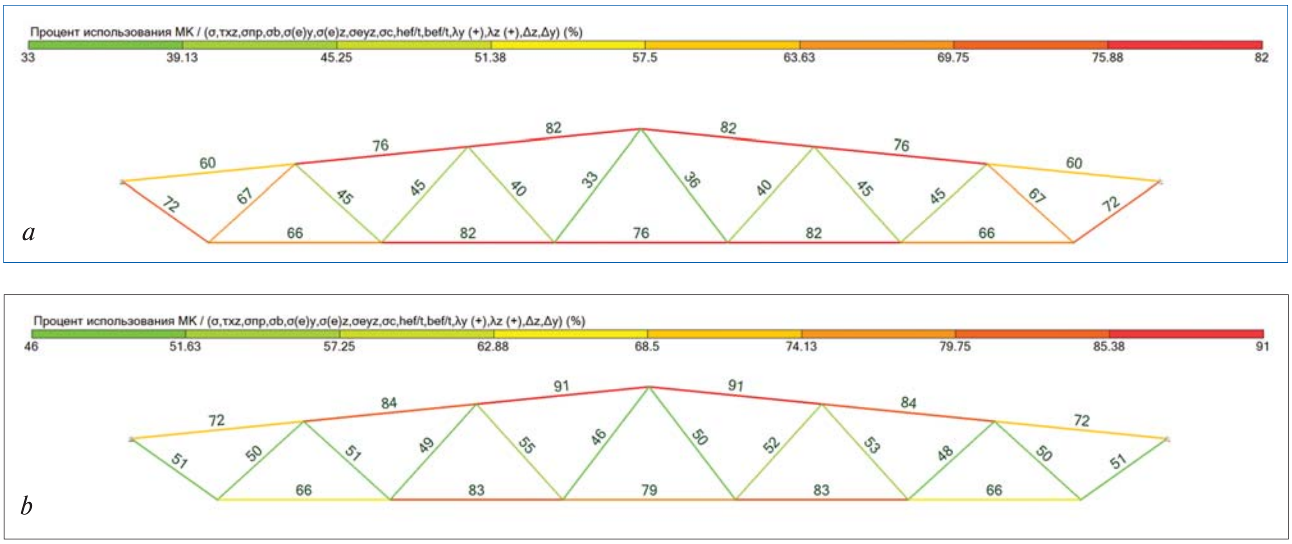


Fig. 4. Mosaics of load-bearing capacity verification for the trusses: *a* — mono-steel (steel S255); *b* — bi-steel (steels S255 + S345)

Table 3. Results of cross-section optimization for the mono-steel roof truss

Element	Cross-section, mm	Length, m	Weight, kg
Top flange	180×140×5	18.1	431.3
Bottom flange 140×5		12.0	248.3
Support diagonals	100×4	7.7	90.3
Web members	80×3	17.94	126.8
		Total flanges:	679.6
		Total web:	217.1
		Overall total:	896.7

Table 4. Results of cross-section optimization for the bi-steel roof truss

Element	Cross-section, mm	Length, m	Weight, kg
Top flange	160×120×4	18.1	303.4
Bottom flange	120×4	12.0	150.7
Support diagonals	100×4	7.7	90.3
Web members	80×3	17.94	126.8
		Total flanges:	454.1
		Total web:	217.1
		Overall total:	671.2

adjustment factors for additional testing and dimensional requirements, as well as a waste coefficient. The truss mass was obtained from the design calculations; the difference in mass reflects the reduction in material consumption achieved by using high-strength steel. The indicators "Materials/kg" and "Factory cost/kg" characterize the relative unit costs per kilogram of the truss mass. A negative difference indicates savings or a reduction in the parameter, while a positive difference indicates an increase in unit costs.

The consolidated results of the comparative assessment are presented in **Table 5**.

The calculations showed that the material cost for a mono-steel truss made of S255 steel is 83,753 RUB, whereas for the bi-steel structure, in which S345 steel is used in the most highly stressed members, this cost decreases to 74,224 RUB, corresponding to a material cost saving of approximately 11.4 %. The labor intensity of fabrication was determined taking into account the construction labor coefficient, the number of primary components, and the truss mass. Thus, the mono-steel truss requires 39.66 man-hours, while the bi-steel truss requires 33.02 man-hours, representing a reduction in labor of 16.7 % (under the given assumptions), mainly due to the lower mass of the truss. The final factory cost of the truss was calculated considering profitability and labor costs. For the mono-steel structure, this amounted to 101,600 RUB, while for the bi-steel truss it was 89,083 RUB, corresponding to a reduction in production cost of 12.3 %. Furthermore, a final assessment of potential savings requires experimentally verified data on technological operations for the specific production process.

The bi-steel index was introduced by the authors as a relative metric to compare the techno-economic parameters of a bi-steel design with a mono-steel one. In this study, the bi-steel index was calculated for key project techno-economic parameters, specifically mass, material cost, labor input, and final manufacturing cost. For the structure under consideration, the most significant improvement observed in transitioning to the bi-steel option is in the mass parameter (index of 0.75), which is the primary driver of overall cost savings. A lesser, though still substantial, improvement in cost-related parameters (indices of 0.83–0.89) is attributed to a certain increase in the unit cost of the high-strength steel. In our view, the proposed bi-steel index could be used in further research for the comparative analysis of various hybrid schemes and for the rapid preliminary assessment of their potential efficacy in the early design stages. For instance, when varying the loading scheme or span lengths, one could compare changes in mass and cost relative to a baseline solution, perform rapid evaluations of different configurations of bi-steel and mono-steel structures, particularly when selecting steel grades for the flanges and the web system, among other applications.

Table 5. Comparative techno-economic indicators of steel trusses made of mono-steel (S255) and bi-steel (S255 + S345) for an 18 m span

Indicator	Mono-steel (S255)	Bi-steel (S255 + S345)	Bi-steel Index*	Difference
Truss weight, kg	896.7	671.2	0.75	−225.5 kg (−25.1 %)
Material cost, RUB	83 753	74 224	0.89	−9 529 RUB (−11.4 %)
Labor intensity, man·h	39.66	33.02	0.83	−6.64 man·h (−16.7 %)
Factory cost, RUB	101 600	89 083	0.88	−12 517 RUB (−12.3 %)
Materials/kg, RUB/kg	93.4	110.6	—	+17.2 RUB/kg
Factory cost/kg, RUB/kg	113.3	132.7	—	+19.4 RUB/kg

* The bi-steel index is defined as the ratio of the corresponding indicator of a bi-steel truss to the indicator of a mono-steel truss (with mono-steel taken as 1.00).

The conducted techno-economic analysis convincingly demonstrates the advantages of bi-steel trusses over mono-steel ones through reduced material consumption, lower labor intensity, and decreased factory cost. It is particularly noteworthy that these results establish preliminary techno-economic grounds for implementing bi-steel trusses in the design and construction of metallurgical workshops and other industrial facilities. Specifically, the methodology of selecting cross-sections based on mosaics of internal forces and displacements to justify the use of mono- or bi-steel configurations can be further extended to roof beams, crane girders, and large-span spatial trusses.

It should be noted that a limitation of this study is the use of numerical modeling for a single truss type without experimental verification and without consideration of fatigue, dynamic, and other factors. In this context, promising directions for future research include full-scale and fatigue testing of bi-steel trusses, investigation of the strength characteristics and residual stresses in connections, development of parametric optimization of cross-sections for different spans, and formulation of regulatory recommendations for the application of bi-steel in real structures.

Conclusions

Based on the results of the conducted analytical studies, the following conclusions can be drawn:

1. The example of an 18-meter-span roof truss shows that combining different steel grades (S255 and S345) provides material economy and retains operational reliability compared to a mono-steel solution (S255). Numerical calculations (LIRA 10.12) showed that the application of high-strength steel in the most highly stressed members allows for a redistribution of internal forces, an increase in load-bearing capacity, and a reduction in the risk of elements exceeding the elastic limit, without altering the structural force scheme. The maximum axial forces for the given loading case occur in the chords: +47 tf (tension) in the bottom chord and –46 tf (compression) in the top chord.

2. The feasibility of using bi-steel trusses is confirmed by techno-economic calculations and comparative analysis, which showed that material costs decrease by 11.4 %, labor intensity by 16.7 %, and the final factory cost of the structure by 12.3 % compared to mono-steel trusses of the same span, while material savings reach 25.1 %.

3. The obtained results are of a modeling nature and can serve as a basis for further experimental verification of the behavior of bi-steel trusses, taking into account fatigue strength, dynamic impacts, cyclic loading, and other relevant factors. Furthermore, during practical implementation, the potential increase in specific labor intensity due to the processing and welding of higher-strength steels must be considered and validated by factory tests.

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