Evaluation of Steel Grade Effects on Stress-Strain Behavior of Joint Connectors: A Finite Element Approach

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The analysis of stress-strain states in the joints of structures, represented by a connector made of two steel plates connected in a "dovetail" manner, has been conducted in this study. The investigation is based on the finite element method (FEM). As an example, the joint structure under static loading conditions is considered. The results presented in the study demonstrate the complex process of changing contact conditions on the connector's contact surfaces. The computational approach used allows for identifying patterns of how the steel grade influences the product's performance. Typically, aluminum-based alloys are used in manufacturing such joints; however, this study suggests the possibility and feasibility of enhancing the efficiency of using such joints by utilizing specific compositions of steel. This study examines various grades of steel, analyzes their stress-strain states under static loads, and evaluates their impact on the strength of structural joints. The research justifies the theoretical possibility of using different steel grades for joints, thereby expanding the range of available options for such joints in general. Numerical simulations were carried out using the ANSYS Workbench 2022 R2 software suite, considering a linear physical model of the materials under investigation, which allows assessing the actual stress states of the structures while considering variations in steel grades. Minimum stress values, both normal (61.96 MPa) and shear stresses (61.02 MPa), were recorded in alloyed steel grade 30Kh. The reduction in stress levels when using grade 30Kh steel compared to aluminum alloy grade D12 amounted to 72.48 % for normal stresses and 71.98 % for shear stresses. Summarizing the research results leads to a scientifically grounded conclusion regarding the feasibility of using alloyed steels for manufacturing connectors to join structures. The trends observed indicate a reduction in material consumption for joints by decreasing connector cross-sections while maintaining their load-bearing capacity.
Key words: steel, aluminium, alloy, strength, stress, constructions, deformation.
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Introduction

Connections are the most critical parts of structures. During manufacturing many connections, holes and notches are made in structural elements, weakening their cross-sections and increasing deformability. The failure of most assembled structures typically starts at the connections [1]. Standard structural solutions for nodal connections often do not allow for the use of new materials and modern technical solutions that could enhance the strength and deformation characteristics of connections. As the span of structures increases, the forces acting on their nodes also increase. Therefore, the load-bearing capacity of a structure is determined by the reliability of the technical solutions for nodal connections.

The connections of metal structures using welding have been studied in works [2–5]. Solutions for joints between steel structures and composite elements have been discussed in works [6-8]. Optimization issues regarding existing structural connection solutions have been addressed in the work [9]. The results of scientific research [10, 11] are dedicated to analyzing the performance of shear connections. Modeling connections in modern software complexes with a focus on studying complex material behavior has been explored in works [12–14]. Experimental investigation issues of joints have been studied in [15–17], and an analysis of their stress-strain states is provided in [18–21]. However, many questions related to studying connections of structures using different materials remain underexplored to date. Therefore, the considered research direction remains quite relevant in the current stage of materials science development.

Aluminum alloy connectors made by the Austrian company Sherpa are well known in the world market [22]. A variety of connector types allows for standardizing joints across different types of structures [23]. A joint connector consists of two steel plates inserted into each other akin to a "dovetail" joint. Experience from abroad indicates that the load-bearing capacity of such joints does not always meet the required standards. The relatively low load-bearing capacity is attributed to the comparatively low strength of the metallic overlays. Thus, the scientific and technical issue addressed in this study revolves around the feasibility of using alternative alloy types as connector materials, including within the context of import substitution and ensuring technological sovereignty.

This study investigates the vertical joints of structures, which are among the most common types of connections. Optimizing the design of joints by reducing their material consumption through a rational selection of materials is a pertinent scientific task that requires an examination of their actual stress-strain state.

The research objective is to enhance the strength, stiffness, and operational characteristics of joints made from various alloys designed for interconnecting structures. The research focuses on joints made from different alloys, with the stress-strain state of these joints being the subject of investigation depending on the material used.

Materials and methods

Numerical modeling was performed using the ANSYS Workbench software suite, implementing the finite element method (FEM). This method involves dividing complex bodies into a specific number of basic elements, while preserving all specified material strength properties. This approach allows for the closest approximation of the objects' behavior to reality while ensuring feasibility for the mathematical solver of the software suite. If there is a continuous variable present in the original object, such as internal stresses in a region, it is approximated by a set of piecewise-continuous functions, which are defined by the boundaries of the basic finite elements. Piecewise-continuous functions are constructed using the values of the continuous variable at the nodes connecting the elements. The prerequisites for using the indicated approach to the study of steel structures using the ANSYS calculation complex are given in [24,25].

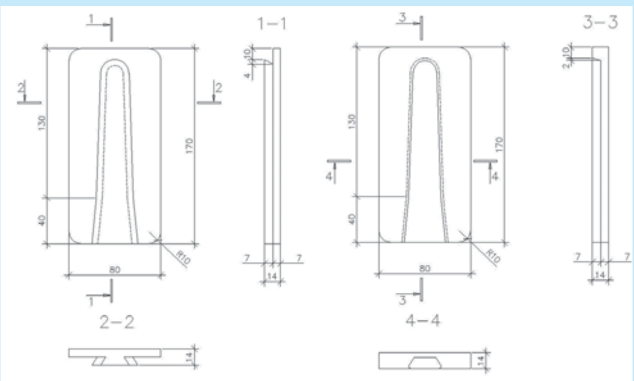
In the majority of cases, the transfer of forces within structures occurs from one element to another through connections facilitated by joints. Scientific investigation of these connections is a highly responsible task as most failures occur precisely at these joint locations. The overwhelming majority of joints are made using steel, with alloys of various grades serving as the material for these connections. The first group of alloys studied comprises structural high-quality carbon steels such as grades 10G2, 30G, and 40G, which are used for manufacturing high-strength components. The second group consists of alloyed steels like grades 30Kh and 18Kh2N4MA. Grade 30Kh is a chromium-alloyed steel utilized for producing fasteners operating at temperatures up to 400 °C, while 18Kh2N4MA is used for manufacturing critical components characterized by high strength, wear resistance, and toughness. It is also employed for components subjected to high dynamic and vibrational loads, operating within the temperature range of –70 °C to +450 °C. One commonly used material for structural joints nowadays is aluminum alloys. Aluminum significantly differs from steel in its properties; it is less rigid and highly ductile while having a lower specific weight. Aluminum-copper-magnesium alloys, with small amounts of manganese (duralumin), are widely used for structural purposes. Specifically, grades D1, D12, and D16 have been studied extensively in this context.

The sketch of the connectors for joining structures is provided in **Fig. 1**. The overall appearance of the connector is depicted in **Fig. 2**.

Fig. 3 shows computer models of the compounds under study. For the most accurate execution of all connection elements, modeling of the joint under study was carried out in the Autodesk Fusion 360 software with subsequent import of the model into ANSYS Workbench.

When modeling the compounds under investigation in the ANSYS Workbench software suite, it is essential to consider the boundary contact conditions of the two plates. For this purpose, contact pairs of the frictional type are used, representing a nonlinear contact that takes into account the coefficient of friction. Within the scope of this study, the values of this coefficient for steel-steel connections are $k_{fr} = 0.42$, and for aluminum-aluminum connections, $k_{fr} = 1.2$.

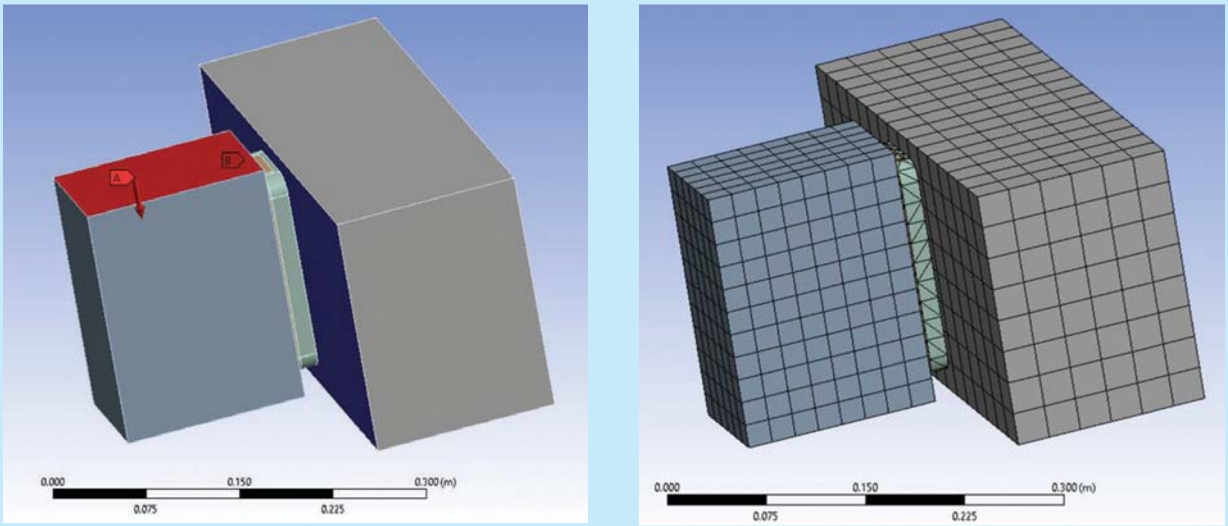
The setting of material properties during modeling was based on information borrowed from the built-in ANSYS



(a) *(b)*

Fig. 1. Sketch of a connector for joining structures:
a) groove-type plate; *b*) spike-type plate

Fig. 2. General view of the connector for joining structures.



(a) *(b)*

Figure 3. Model of the studied joints: (*a*) in the Autodesk Fusion 360; (*b*) in ANSYS Workbench

Table 1. **Physico-mechanical characteristics of the considered alloys**

Alloy grades	Standard	Density, kg/m³	Strength, MPa	Coefficient of thermal expansion, 1/degree	Young's modulus, MPa
Group 1 – High-quality carbon structural steel					
10G2	1050-2013	7790	440	11.3	2.04
40G		7810	590	11.1	2
30G		7810	540	12.6	2.04
Group 2 – Alloyed structural steel					
30Kh	4543-2016	7820	880	12.4	2.08
18Kh2N4MA		7950	1130	11.7	2
Group 3 – Aluminum deformable alloy					
D1	4784- 97	2800	370	22.9	0.72
D12		2720	220	22.9	0.72
D16		2770	420	22.9	0.72

Workbench database. **Table 1** presents the physico-mechanical characteristics of the investigated alloys grouped accordingly.

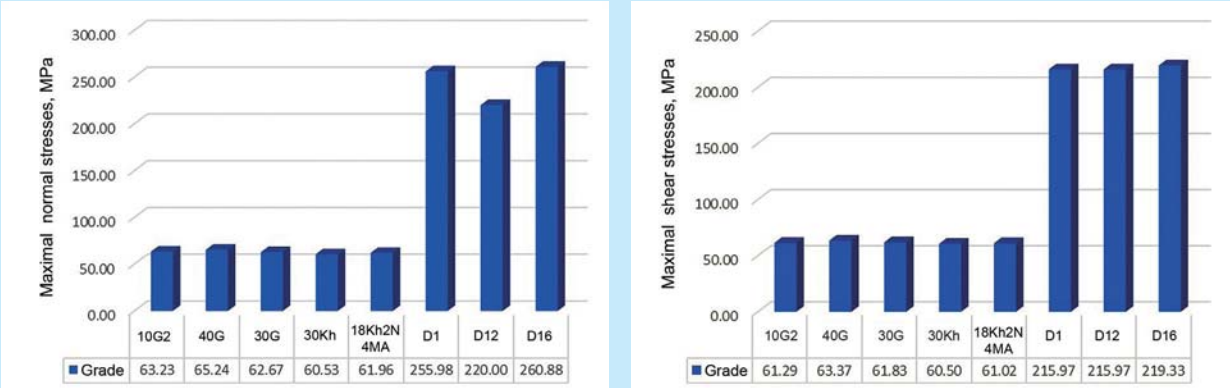
Results and discussion

Based on the results of numerical analysis of the joint of structures with variations in different alloy grades, the values of maximum normal stresses, shear stresses, and deformations in the material under deformation were determined. The ultimate deformation corresponding to the limit allowable state, at which the integrity of the joint is compromised and further safe operation is no longer feasible, was set at 7 mm. This level of deformation is assumed to be equal to the size of the support area, since if the requirement for minimal support of the supporting part on the supported part is violated, the abutting structural elements are completely destroyed. Histograms depicting the values of normal stresses and shear stresses at which the integrity of the joint of the structure is compromised are presented in **Fig. 4**.

Mosaics of stresses at the joints of structures for various types of alloys are shown in **Fig. 5**.

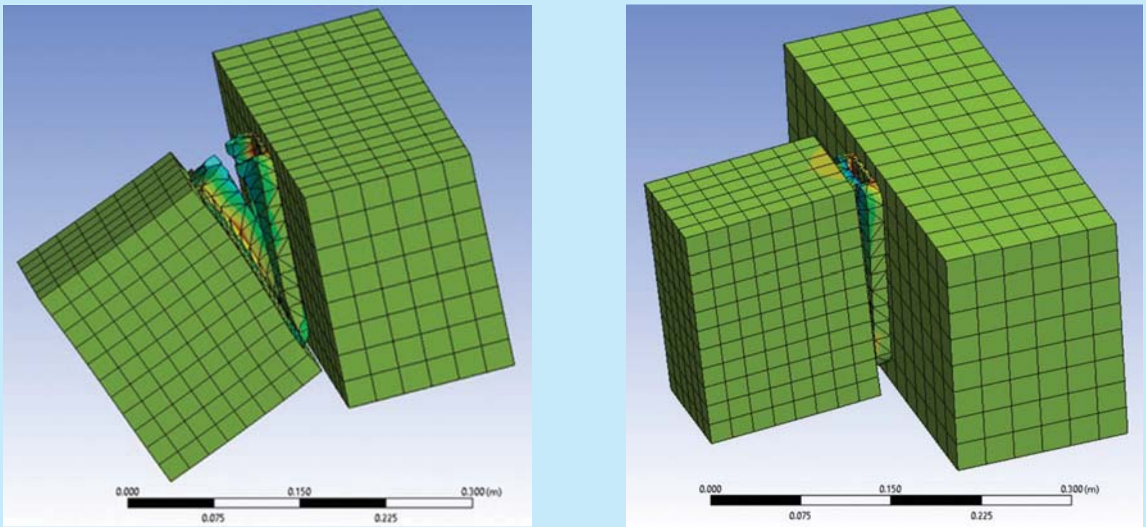
The nature of the destruction of a joint connector made of D12 aluminum alloy and 30Kh steel when reaching limiting deformations characterizing a complete violation of its integrity is shown in **Fig. 6**. The destruction began as a result of rotation of the supported part relative to the supporting one in the upper zone of the joint and occurred due to the collapse of the contact surfaces.

The analysis of research results demonstrates that variations in steel grades for connector materials significantly impact the structural strength characteristics of joint constructions under constant loading. The use of alloyed steels instead of aluminum alloys for connector material enhances



(a) *(b)*

Fig. 4. Histograms of maximum values of the studied parameters at the joints of structures: *a*) normal stresses, MPa; *b*) shear stress, MPa



(a) *(b)*

Fig. 5. Mosaics of normal stresses at the joint: (*a*) for alloy D12;(*b*) for alloy 30Kh

the operational safety by reducing stress levels. Stress reduction achieved by employing an alloyed steel grade 30Kh compared to aluminum alloy grade D12 amounts to 72.48 % for normal stresses and 71.98 % for shear stresses.

The ultimate normal stresses of the investigated steel in the 1st group ranged from 62.67 to 65.24 MPa, with their maximum strength values at 440–590 MPa, resulting in a material loading level at the ultimate state of 9–14 %. Stresses in the 2nd group of steels ranged from 60.53–61.96 MPa, with a loading level of 5–7 %. The maximum loading level was observed in aluminum alloys – 62–100 %, with ultimate normal stresses of 220.00–260.88 MPa.

Summarizing the above, it can be concluded that grade 30Kh steel is recommended as the material for manufacturing the investigated joints. The advantage of using this grade alloy over traditional aluminum alloys is the reduction in material consumption of the connector due to the decreased cross-sectional dimensions while maintaining its load-bearing capacity. The type of joints under study can be used to connect structures made of various materials (wood, concrete and steel).

The economic analysis of the efficiency of using connectors made from alloyed steel grade 30Kh was conducted based on modeling cash flows from single-product manufacturing. We evaluate the effectiveness on the basis of M25 (Sherpa) connectors made of aluminum alloy. The simulated financial parameters are shown in **Table 2**.

The project's efficiency is assessed through two main avenues: the introduction of a new product – a connector made from alloyed steel grade 30Kh with a forecast of cash flows over 5 years, and accounting for a consumer effect of 99.07 rubles per unit, which should stimulate increased demand for the product due to significant cost savings for potential consumers.

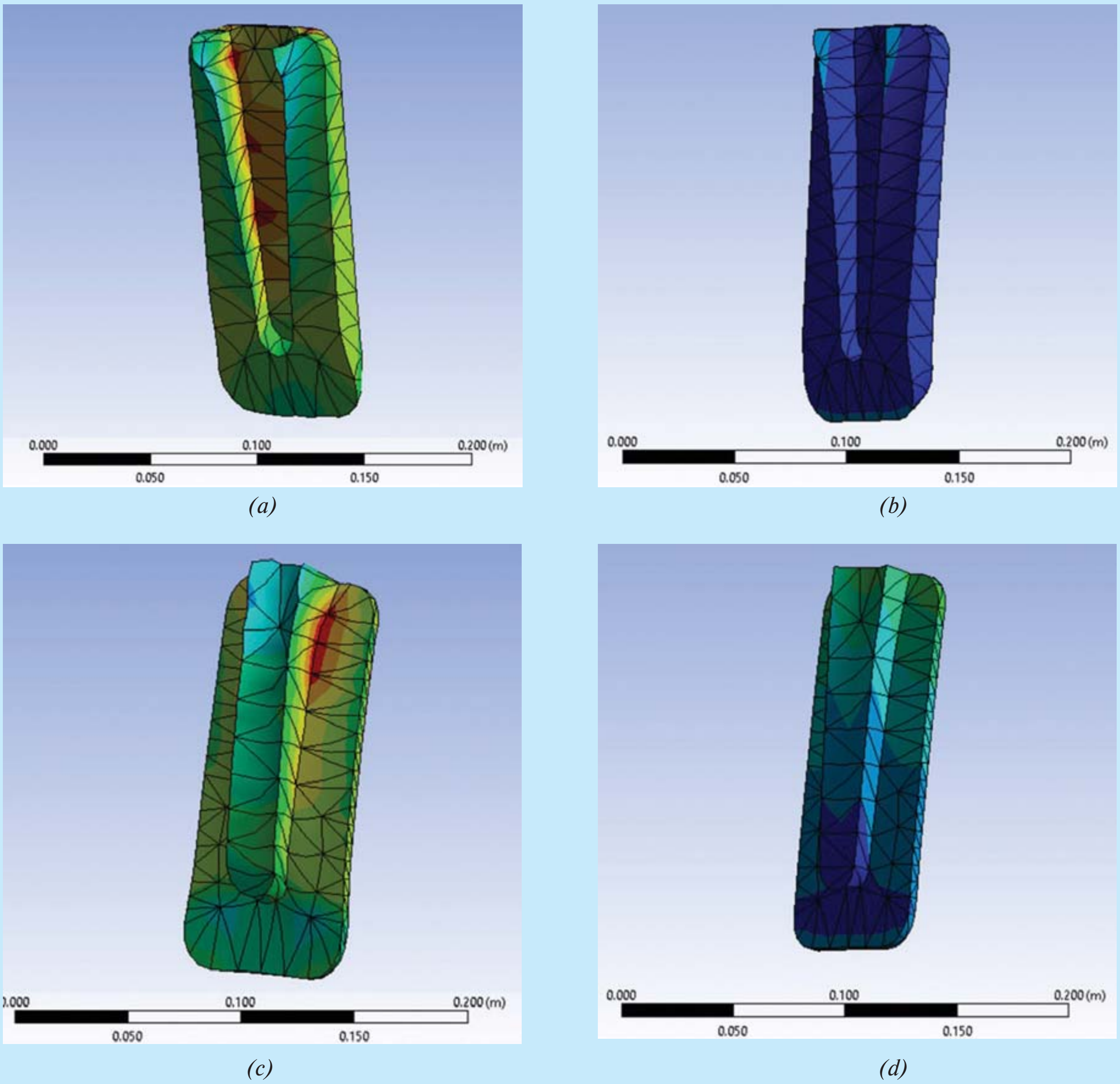


Fig. 6. Nature of destruction of the butt parts of connectors (supporting and supported parts) in the limit state: (*a*), (*c*) D12; (*b*), (*d*) 30Kh.

Table 2. **Parameters included in the financial model**

Parameters per unit	Connector based on steel 30Kh (analogous to Sherpa M25)	Connector Sherpa M25
Current selling price (including VAT)	153.00 rub/pcs.	252.07 rub./pcs.
Labor costs	28.74 rub.	n/a
Depreciation rate	4.68 rub.	n/a
Material costs	37.00 rub.	n/a
Overheads	10 %	n/a
Marketing expenses	10 %	≈25 %

The financial model incorporates a minimum selling price of the product at 153 rubles per unit including VAT. Labor costs are calculated based on the wage of one worker at 46,086 rubles, corresponding to the average regional value in the Vladimir region. Additionally, surcharges are included at the same amount. Thus, the labor costs per unit of production amount to 28.74 rubles per unit. The existing cost level allows for a substantial increase in this threshold. Material costs amount to 37 rubles per part. The model also includes expenses for other costs at 10 %, as well as promotion and marketing expenses at 10 % of revenue.

Table 3. **Estimated financial indicators of the project for five years**

Indicator	Connector (steel grade 30Kh)
Total revenue, thousand rubles	53 176
Production costs, thousand rubles	27 928
Earnings before interest and tax (EBIT), thousand rubles	13 570
Economic effect of savings for consumers per year, thousand rubles	4 965
Investments, including working capital, thousand rubles	3 700
Total cash flow, thousand rubles	11 370
Net present value (NPV), thousand rubles	5 656
Discounted payback period, years	1.58
Internal rate of return, %	219.8 %
Modified Internal Rate of Return (MIRR), %	81 %
Profitability Index (PI), rubles	6.39
Budgetary efficiency, thousand rubles	12 162
Average break-even point of new technology, thousand rubles	5 698
Average return on sales, %	19.4 %

The assessment of efficiency is conducted using a project-based approach with relevant indicators. As a result of the financial modeling conducted, the following comprehensive results of the economic efficiency assessment of introducing connectors made of 30Kh steel instead of aluminum alloys are presented in **Table 3**.

The Net Present Value (NPV) of the project amounts to 5.7 mln rubles with an investment volume of 3.7 mln rubles. The discount rate is set at 24.67 % for all products. The discounted payback period varies and stands at 1.58 years, while the simple payback period is 1.46 years. The Internal Rate of Return (IRR) for the project is 219.8 %, and the Modified Internal Rate of Return (MIRR) is 81 %. The Profitability Index (PI) of discounted cash flows for the project is 6.39, indicating that for every ruble invested, there will be an economic savings effect of 6.39 rubles. The cumulative forecast budgetary efficiency reaches 12.2 million rubles, which is a significantly high forecast indicator. The average return on net economic profit is projected to be 19.4 %, demonstrating the effectiveness of implementing the proposed solutions.

Based on the results of the modeling, the following recommendations can be made regarding the practical application of the obtained results: in the context of joints, it is possible to use alloyed steels instead of aluminum alloys for manufacturing connectors. This substitution offers a real opportunity to reduce the geometric dimensions of the connectors while maintaining overall load-bearing capacity. The technical and economic significance of these results lies in expanding the range of steel grades recommended for manufacturing connectors to execute structural joints.

Conclusion

The work establishes the theoretical feasibility of using different grades of steel, distinct from traditional aluminum alloys, for manufacturing connectors joining structural components. Based on numerical investigations of joints made from various alloys, the following conclusions can be drawn:

1. Numerical studies of structural joints were conducted using the ANSYS Workbench computational software, with variations in different alloys. A finite element model of the joint was constructed, resembling two plates contact-fused at the node in a “dovetail” fashion.

2. A qualitative and quantitative assessment of maximum stress fields in the joint was obtained. The highest stresses in the joint material, reaching the joint’s ultimate displacement, were observed in aluminum alloys, with the strength limit of the D12 alloy at 220 MPa being fully exhausted. Minimal stresses, both normal (61.96 MPa) and shear (61.02 MPa), were recorded in alloyed steels (such as grade 30Kh). The strength characteristics of structural carbon steels were close to alloyed steels. Thus, the reduction in stress levels when using grade 30Kh steel compared to aluminum alloy D12 amounted to 72.48 % for normal stresses and 71.98 % for shear stresses. Grade 30Kh alloyed steel is recommended as the material for manufacturing joints of the studied type, offering real prospects for reducing overall material consumption by reducing the cross-sectional dimensions of connector elements.

3. Under limit conditions, the material load levels for the investigated steels in the first group (grades 10G2, 30G and 40G) ranged from 9% to 14%, for the second group (grades 30Kh and 18Kh2N4MA) from 5% to 7%, and for the third group (grades D1, D12, and D16) from 62 % to 100 %. An assessment of the economic efficiency of implementing grade 30Kh steel connectors instead of aluminum alloys indicates an increase in average profitability to 19.4 %.

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