Strength and deformability of lightweight metal trusses with elements from cut I-beams

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Abstract. The article is devoted to the study of the strength and deformability of light metal trusses with elements made of cut I-beams based on experimental tests. A truss design is proposed based on the idea of a waste-free technology for obtaining the maximum number of truss elements in the process of cutting the initial billet—a rolling I-beam. The manufacturing technology of the farm, research tasks and test samples are described. The developed and manufactured designs of truss models were a geometric similarity of trusses with parallel belts with a span of 24 m, a cross-section height along the shelves of the belts-2.4 m, with the length of the belt panels equal to 3 m, calculated for different loads. The analysis of the obtained results showed that the theoretical values of axial stresses in the elements of truss models differ from the values of experimental axial stresses in General by no more than 8%. According to the results of numerical studies of the stress-strain state of trusses in the elastic stage of their operation, it was established: - truss structures have sufficient stiffness and strength (the coefficient of load-bearing capacity was a value that varies for trusses of various series within the range of 1.34 – 1.7); - the stress values in the truss elements calculated during the processing of the results of numerical studies have a large similarity with the stress values calculated on the basis of experimental data.

1. Introduction

Scientific and technical progress in the field of construction is closely related to the problems of development and improvement of steel structures. With the correct use of achievements, it is possible to reduce the material consumption of building metal structures by about 10-20% and simultaneously increase labor productivity by more than twice during manufacture and by 70% during installation [1-7].

In increasing the industrialization of construction, the most important place is given to the introduction of light metal structures. Reducing the weight of structures leads to a reduction in material consumption and reduced transport costs. This is especially true for the development and implementation of new lightweight structural materials as well as the enhancing properties of the existing ones [8-10]. Pre-Assembly and block installation of coatings are also possible. Labor productivity in the Assembly of coatings increases by 25-30%, and during installation by 1.5 times.
Installation time is reduced by 15-20% [11-17]. Further improvement of the process of designing, manufacturing, complex delivery and installation of light metal structures of industrial buildings requires a combination of optimal mass indicators with minimal labor intensity of mechanized production. The desire to combine these factors makes it rational to use structures made of tubular, thin-walled, bent and t-shaped profiles. Technical and economic analysis of the coatings of industrial buildings with a span of 18 and 24 m shows that the best indicators are trusses with belts of pipes and brands [18-20]. The proposed truss designs are based on the idea of a waste-free technology for obtaining the maximum number of truss elements in the process of cutting the initial billet—a rolled I-beam. Some results of research on trusses under development are presented in [21, 22]. Fig. 1 shows the simplest technological sequence of manufacturing a truss that can be used in production.

![Diagram of truss production](image-url)

**Figure 1.** Technological sequence of truss production: 1 – dissolution of the original I-beam along the main and additional lines; 2 – sliding elements; 3 – ready truss, where is the length of the brace; R – length strip element (stretched brace); α – angle of inclination of the sections of the cut lines forming the side edge gussets; h – section height of the original I-beam; H – height of the truss.

According to the developed technology of manufacturing trusses allows us to efficiently cut the initial billet and get a cross section of belts and struts with an area close to the minimum required, determined from the condition of their strength under the calculated forces. From figure 1.14 it is evident that the pattern of the workpiece allows to increase the cross section of the belt from the supports truss to the middle of the span and reduce at the same time, the cross section of the struts, i.e. the use of the proposed technology the manufacture of truss provides the distribution of material between the truss elements close to the optimum, which reduces a lot of trusses. Another important advantage of the new truss design is to reduce the number of main and additional elements, as well as the length of welds. From one billet are obtained simultaneously belts with tides that serve as styles, and stretched bars of the grid. This reduces the number of standard sizes of the main parts to 2 – 4,
while in traditional trusses it reaches 5-9. Reducing the length of welds is mainly due to the formation of shapes in the process of cutting the workpiece and eliminating the need for welding.

### 2. Methods

One of the most accessible and effective methods of research of the considered design solutions is their modeling.

The research on models of trusses with elements made of cut I-beams aimed to solve the following questions experimentally with minimal material costs, minimal labor intensity and cost of experimental research:

- study of the stress-strain state of trusses under load;
- specification of coefficients of working conditions of various elements of trusses for their use in the calculation of engineering method;
- determination of the actual carrying capacity of trusses and their carrying capacity reserve coefficients;
- identification of factors that affect the conditions for the transition of trusses to the limit state;
- study of the operation of truss nodes.

The analysis of geometric characteristics of cross sections of truss elements - belts of brands and grilles of strip elements, as well as paired corners for compressed grating rods in the range of existing grades showed that the geometry of their cross sections obeys with a sufficient degree of accuracy forty-two scale factors used in modeling rod structures.

This allowed us to apply the method of mechanical modeling using geometric similarity with the main scale factors when designing truss models.

When modeling full-scale trusses intended for a large range of design loads, but designed using not very different from each other calibers of rolling I-beams required for the manufacture of models, different scales were taken. The scale of six models was assumed to be 1:4 and the scale of three models was 1:2.

The developed and manufactured truss models were geometrically similar to trusses with parallel belts with a span of 24 m, a cross section height along the belt shelves of 2.4 m, with a length of 3 m of belt panels designed for different loads. Three series of truss models were prepared for experimental research, with three trusses in each series.

Of the model trusses of the first series in the amount of three pieces performed at the scale of 1:2, had a span of 12 m, the height of the cross section on the outer faces of the belt 1.2 m and the length of the panel zone of 1.5 m. These models were made of rolled I-beam № 20 B1, the material I-beams - steel S345. The truss models of the first series had a constant cross-section of the belts along the length of the trusses, as well as the same cross-section of the stretched bars of the grid.

Models of trusses of the second and third series in the number of three trusses in each series were made on a scale of 1:4, had a cross-section height of 0.6 m and a length of 0.75 m belt panels. Three models of them were also made of rolled I-beam No. 20 B1, the material of the I-beams is steel C255.

Truss models were tested with a nodal load. Loading of models was carried out by piece loads weighing 10-30 kg, stacked on platforms. The weight of the cargo was selected based on the calculation of providing ten stages of loading models to the design load. The calculation schemes of the tested truss models are shown in Fig. 3.1. When conducting experimental studies of trusses on models, the maximum deflections of trusses in the middle of their span, stresses and deformations of the extreme fibers of the cross sections of rods, stresses in nodal shapes, movements of individual sections of the upper belt panels in the plane of the trusses, rotation angles of individual nodes of the truss models were determined.

The other three models were made from rolled I-beams No. 16, material-steel C375. In the models of these trusses, the cross-section of the belts varied within the dimensions of the shapes in the section adjacent to the second and third panels of the belts. The compressed bars of the grids in all models were made of paired equal-field corners connected for joint operation by connecting gaskets made of...
sheet steel. The material of the corners is C245 steel, with the calculated resistance of steel \( R_y = 2450 \) kg/cm\(^2\).

3. Results and discussion

In order to obtain reliable results of experimental studies of the work of trusses with elements from cut I-beams, three series of truss models were tested, as noted above, three trusses in each series. The calculated nodal load for each series of truss models tested was determined by the bearing capacity of the weakest element.

For truss models of the first series, the calculated nodal load was determined from the load capacity condition of the most loaded (middle) panel of the upper belt; for truss models of the second series - from the load capacity condition of the lower belt, and for truss models of the third series - from the load capacity condition of the stretched rasp.

Data on the geometric characteristics of cross sections and the load-bearing capacity of the tested truss models are shown in table 1. Given that a significant number of truss models have been tested, it is not appropriate to stop at analyzing the test results of each individual model. Therefore, when analyzing the experimental data, we will talk about the average arithmetic value of the test results for each series of trusses calculated during statistical processing.

The values of maximum and minimum experimental stresses within the cross-section height of the elements were calculated based on the results of the strain-resistor readings in the characteristic cross-sections of the truss elements. Plots of experimental forces in the first series of truss models based on the calculated forces \( N \) and \( M \) are shown in Fig. 3.

To compare the obtained experimental forces in the elements of truss models from the calculated node load in the elastic stage of their operation with the theoretical forces, the calculation of truss models on a computer using the finite element method using the standard program "Lira 10.10" was performed. The calculations took into account the design scheme of trusses with rigid coupling of elements in nodes.

The results of calculating the values of experimental and theoretical stresses in the elements of truss models are summarized in table 1 (the table shows the average data for the three truss models). The dependence of the maximum deflection of truss models on the value of the node load is shown in Fig. 3.
Table 1. Results of calculating experimental values and theoretical stresses

| Element | Rod designation | № cross section | Stresses σ and test coefficients K in the truss elements from the design load in the elastic stage of operation | Axial stress | Bending stresses | The total voltage |
|---------|-----------------|-----------------|-------------------------------------------------------------------------------------------------|------------|-----------------|-----------------|
|         |                 |                 | | σнм | σт | σнм/σт | σнм | σт | σнм/σт | σнм | σт | σнм/σт |
| upper belt | 1 | -300 | 8 | 0.79 | -35 | -34.7 | 1.008 | -335 | -414.5 | 0.81 |
|           | 2 | -443 | - | 1.166 | 58 | 67.9 | 0.85 | -385 | -311.9 | 1.2 |
|           |               |                 | 379. |
| B1       |                 |                 | | 1 | 1023 | 1029 | 0.99 | 2.9 | 2.2 | 1.3 | -1020.1 | 1026.8 | 0.99 |
|           | 4 | - | - | 0.975 | 76.1 | -69 | 1.1 | -1073 | 1037.4 | 0.977 |
|           | 1004 | 1029 | | 294 | 266 | 1.1 | -738 | -1098 | 0.967 |
|           |                 |                 | 763 |
| B2       |                 |                 | | 3 | 1690 | 1680 | 1.005 | 30.4 | 44 | 0.7 | -1659.6 | - | 1.01 |
|           | 6 | - | 1680 | 1.005 | 89.8 | 61.8 | 1.4 | -1538.2 | - | 0.95 |
|           | 1628 | | | 347 | 239 | 1.4 | 1281 | 1618.2 | 0.89 |
|           |                 |                 | -1441 |
| B4       |                 |                 | | 7 | 894 | 830 | 1.07 | -45.1 | -56.36 | 0.8 | 848.9 | 773.6 | 1.097 |
|           | 8 | 895 | 830 | 1.07 | 37 | 79.5 | 0.5 | 932 | 909.5 | 1.02 |
|           | 9 | 1543 | .7 | 1.08 | 2.2 | 2.9 | 0.76 | 1545.2 | 1425.6 | 1.08 |
| lower belt | 1 | 1496 | 1422 | 1.05 | 76.2 | 55.2 | 1.38 | 1572.2 | 1477.9 | 1.06 |
|           | 0 | 315.4 | 228.4 | 1.38 | 1811.4 | 1651.1 | 1.09 |
| H2       | 7 | 1887 | 1897 | 0.99 | 45.6 | 40.0 | 1.14 | 1932.6 | 1937 | 0.99 |
|           | 1 | 1901 | 1897 | 1.002 | 45.6 | 40.0 | 1.14 | 1946.6 | 1937 | 1.005 |
|           | 2 | 189 | 164.3 | 1.15 | 2090 | 2061.3 | 1.014 |
|   |   |   |   |   |   |
|---|---|---|---|---|---|
| P1 | 1 | 2122 | 239.3 | 206.2 | 1.16 |
| 3 | 2085 | .4 | 0.98 | 239.3 | 206.2 | 1.16 |
| 1 | 1984 | 2122 | 0.93 | -90.3 | -92.6 | 0.97 |
| 4 |   |   |   | -90.3 | -92.6 | 0.97 |
|   | 1 | 1512 |   |   |   |   |
| P2 | 5 | 1454 | .3 | 0.96 | 217.6 | 244.3 | 0.89 |
| 1 | 1485 | 1512 | 0.98 | -153.3 | -136.4 | 1.12 |
| 6 |   | .3 |   | -153.3 | -136.4 | 1.12 |
|   | 1 | 907. |   |   |   |   |
| P3 | 7 | 906 | 9 | 0.99 | 177.8 | 199.3 | 0.89 |
| 1 | 912 | 907. | 1.004 | -65.5 | -72.5 | 0.9 |
|   | 9 |   |   | -65.5 | -72.5 | 0.9 |
|   | 1 | 302. |   |   |   |   |
| P4 | 9 | 301 | 7 | 0.99 | 150.4 | 157.5 | 0.95 |
| 2 | 308 | 302. | 1.017 | -15.3 | -16.6 | 0.92 |
|   | 7 |   |   | -15.3 | -16.6 | 0.92 |

|   |   |   |   |   |   |
|---|---|---|---|---|---|
| C1 | 1 | -940 | 1226 | 0.77 | 62 | 58.8 |
| 2 | -925 | - | 0.75 | -62.1 | -67.2 | 0.92 |
| 2 | 1226 |   |   | -105.3 | 114.04 | 0.92 |
|   |   |   |   |   |   |   |
| C2 | 3 | -686 | -877 | 0.78 | 69.8 | 75.1 |
| 2 | -672 | -877 | 0.76 | -57.7 | -45.9 | 1.25 |
| 4 |   |   |   | -97.8 | -78.0 | 1.25 |

|   |   |   |   |   |   |
|---|---|---|---|---|---|
| C4 | 5 | -235 | 3 | 1.04 | 18.8 | 20.0 |
| 2 | -231 | - | 1.03 | 16.4 | 17.9 | 0.92 |
| 6 | 224. |   |   | 23.5 | 25.6 | 0.92 |

Note: The table represents data for stretched struts and stands.
The analysis of the obtained results shows that the theoretical values of axial stresses in the elements of truss models differ from the values of experimental axial stresses in general by no more than 8%.

The test coefficient $K$ for axial stresses, defined as the ratio of the measured stress values $\sigma_t$ to the theoretical stress values $\sigma_t$, was 0.965 - 1.08. The exception is the extreme panel B1 of the upper belt of truss models of the first series, for which the test coefficient in section 1 and 2 (along the edges of the panel) is 0.79 and 1.16, and the struts C1 and C2, for which the coefficient is 0.77 (0.75) and 0.78 (0.76), respectively. A significant discrepancy between the theoretical and experimental values of axial stresses in the extreme panel of the upper belt is explained by the large influence of the deformed state of the truss model on the support node, which has a smaller number of converging elements in it in comparison with the intermediate nodes.

At the same time, the theoretical values of bending stresses in General are significantly less than experimental stresses, which can be explained by the influence of the deformed state of truss models on the formation of bending moments in their elements. The test coefficient for bending stresses was 0.7 - 1.4.

Due to the significant value of the axial stresses in relation to the bending stress, the total theoretical stresses were close in value to the experimental ones. The test coefficient for total stresses in the elements of truss models was 0.85 - 1.09.

Thus, the rigidity of nodes in trusses with elements of cut I-beams leads to the appearance of bending moments in the truss elements (noticeable in asymmetric sections relative to the bending plane), which require their consideration when checking the truss elements for strength and stability.

Stresses from bending moments in elements of truss models are insignificant in the span and increase in the supporting zones. Maximum uniformity of stress distribution along the height of member cross-sections characterizing the impact of rigidity on the stress state of the elements, it is possible to estimate in percent as the ratio of the magnitude of bending stress to axial stress. According to experimental data, the unevenness of the stress distribution for various elements of truss models is up to 22% in the most stressed stretched bars, 5.3-35.3% in compressed belts (a large value is for the walls of brands), 2.1 – 28.8% in stretched belts, and 5 – 15% in compressed bars.

As shown by experimental studies, the actual vertical movements of nodes (lower belt) of truss models are slightly behind the calculated theoretical values. The deviation of experimental values of node movements from the theoretical ones was 3 -5%. For fig. 3 shows a graph of the dependence of

![Figure 3. Dependence of the maximum deflection of truss models on the value of the node load](image)
the deflections of the middle nodes of the lower belt of truss models on the load. The first section of
the curve that characterizes the elastic operation of truss models follows a linear law. In the second
section, the proportionality is violated: the increments of deformations outstrip the increments of load.
At the calculated node load, the average maximum value of the experimental deflection was 26.5 mm,
and the theoretical value was 28.34 mm. The test deflection coefficient for the first series of truss
models was: \( K = 0.935 \).

The transition of the truss models of the first series to the limit state occurred due to the loss of
stability of the middle panels of the upper belt from the plane of the truss models. At the calculated
node load of the \( R_{\text{calc}} = 20.64 \text{ kN} \) the average value of the relative deflection of the trusses was \( f / 1 = 1 / 424 \), which is significantly less than the allowable deflection equal to the trusses \( [f / 1] = 1 / 250 \).

The destructive node load averaged 36.15 kN and exceeded the calculated load by 1.7 times. The
flexibility of the upper belt of truss models: the first series in the plane of the truss is higher than the
flexibility of it from the plane of the truss models. Under this circumstance, it would be expected that
the upper belt of the first series of truss models would lose stability in the plane of the truss models,
and not from their plane. The loss of stability of the upper belt of the truss models of the first series
from the truss plane can be explained by a number of reasons. First, the restraining effect of node
stiffness on the stability of upper belt panels in the plane of truss models, leading to a decrease in the
coefficient of the calculated length of panels, and, secondly, the stimulation of the deformed state
of the upper belt to the loss of stability, as was justified above, in the skew-symmetric form (according
to the second deformed scheme). With this in mind, the next step is calculation of the stability of the
upper belt models of trusses in plane with the ratio of the estimated length \( h = 0.7 \) and the calculation
of the stability of plane models span coefficients \( \mu = 1 \).

The results of determining experimental and theoretical stresses in the models of the second series
confirmed the similar nature of the stress distribution over the height of the cross-section of elements,
which makes it possible not to repeat the analysis of their stress state. The safety factor for bearing
capacity for model trusses of the second series amounted to the value of 1.37.
With a calculated node load of 25.7 kN, the truss models had a deflection equal to 1.94 cm (1/309 of
the span). With a standard load of 18.56 kN, the maximum deflection of the truss models was 1.25 cm
(1/480th of the span), with a standard deflection of 1/250th of the span (in the absence of lifting and
transport equipment). Truss models of the second series went into the limit state due to the loss of
stability of the middle panels of the upper belt.

The experimental data of the model trusses of the third series showed that the distribution of effort
in their elements is similar to the distribution of forces in elements of the model trusses of the first and
second series. The transition of the trusses to the limit state occurred due to the loss of stability of the
middle panels of the upper truss belts. Additional studies of the deflections of third-series truss models
along the length of their span have shown that they also have a sufficient margin of strength and
rigidity.

The experimental data obtained confirm the theoretical studies carried out to assess the possible
form of stability loss of the most loaded (middle) panels of the upper belt, taking into account their
deformed scheme. This circumstance provides a reserve of stability of the compressed elements of the
belts, which can be taken into account when improving the truss designs in the future. It should be
noted that if it is possible to reduce the coefficient of design length for the middle panels of the upper
belt, you can provide 6% savings in steel.

4. Conclusions
The design of the truss allows you to make belts of tidal cross-section for trusses with tides on their
walls, serving as styles, and stretched bars of the grid in the form of strips cut out of the I-beam wall in
the areas between tides. The connection of the stretched bars of the grid is performed butt-to-butt with
the side edges of the shapes.

This design allows you to make a truss with a rational distribution of steel between the belt panels
and the stretched bars of the grid in accordance with the law of force changes in these elements and
reduce the weight of the truss by 14-20% compared to the used truss designs. This minimizes the number of different calibers of the original rolling profiles to 2-4 and the number of basic Assembly elements required for the manufacture of the truss.

By eliminating the operation of pre-preparation of shapes and their welding, as well as reducing the connecting gaskets, the number of additional Assembly parts and the length of welds is reduced. In new truss designs, stretched lattice rods have increased flexibility from the truss plane, so their use is not allowed in buildings with dynamic loads directly applied to the trusses. In this regard, the use of developed trusses is recommended in buildings without overhead cranes.

Based on the results of numerical studies of the stress-strain state of trusses in the elastic stage of their operation, it is established:

- truss structures have sufficient rigidity and strength (the coefficient of load-bearing capacity was a value that varies for trusses of different series in the range of 1.34-1.7);
- the stress values in the truss elements calculated during the processing of the results of numerical studies have a great similarity with the stress values calculated on the basis of experimental data.

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