SECTION «STATE ADMINISTRATION»

COMPREHENSIVE ASSESSMENT OF THE STRENGTH OF LOAD-BEARING BEAMS IN TRANSPORT STRUCTURES, TAKING INTO ACCOUNT THE THERMOMECHANICAL AND TECHNOLOGICAL EFFECTS OF PRELIMINARY STRESSING

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Abstract. The monograph section is devoted to the development of analytical and engineering methods for assessing the residual life of steel beams that are pre-stressed by thermal action. The study focuses on load-bearing beams of railway freight cars (centre sills), which are manufactured by welding and often suffer from welding distortions and reduced load capacity. *The purpose* of the paper is to establish quantitative indicators of beam resource according to the criteria of load-carrying capacity (first limit state), stiffness (second limit state) and technological efficiency (reduction of welding deformations). *Methodology* of the study is based on the theory of elasticity and plasticity, the hypothesis of plane sections, the Prandtl stress-strain diagram, differential equations of the elastic line, and energy methods for determining ultimate moments. Analytical expressions are derived for conventional and pre-stressed I-beams, and a mathematical model of thermal reverse bending is developed to compensate for welding deformations. Numerical calculations are performed for typical spans (up to 12 m) and loads. *Results* of the survey showed that the load-carrying capacity of pre-stressed beams increases to 153.2% compared to conventional beams. Stiffness improves by 19.4% (simply supported) or up to 80% (fixed ends). The height of a pre-stressed beam can be 1.847 times smaller for the same load capacity, saving up to 25% of steel. Thermal reverse bending (heating

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to 550–650 °C) reduces welding-induced deflections by 23–31% with pre-stress losses of only 14–23%. *Practical implications.* The developed models and engineering recommendations allow designing lighter and stiffer steel beams for transport structures, implementing thermal straightening in wagon manufacturing (tested at Karpatu and Kryukiv Railway Car Building Works), and reducing the rejection rate from 18% to 4%. *Value/originality.* For the first time, a comprehensive resource assessment is performed for pre-stressed steel beams that simultaneously accounts for thermomechanical loading during manufacture and the compensation of welding deformations, filling the gap between traditional structural analysis and real technological processes.

Introduction

Load-bearing beams of transport structures (railway rolling stock, car frames, etc.) are operated under conditions of a complex combination of force and temperature loads. Among the latter, thermal influences occupy a special place – temperature fluctuations due to climate changes, solar radiation, repair heating or engine operation. These factors significantly affect the stress-strain state of beam elements, and therefore, their resource.

Underestimation of thermal preload (both technological and operational) can lead to unpredictable deformations, the emergence of residual stresses and premature failure of structures. This is especially true for long-span load-bearing systems of transport structures, where thermal deformations reach significant values, which threatens operational safety and causes economic losses.

The problem of increasing the service life of steel structures is one of the central ones in modern transport engineering and infrastructure industries. Beam elements, working mainly in bending, form the basis of load-bearing systems of building frames, bridges, gantry cranes, railway cars and other structures. Traditional solutions often lead to excessive metal consumption or insufficient durability due to limitations in load-bearing capacity, stiffness or crack resistance.

One of the most effective ways to increase the load-bearing capacity and durability of freight car elements is prestressing, which allows you to create initial stresses in the structure that are opposite in sign to the operational ones. For thin-walled steel beams used in the backbone and side load-bearing structures of wagons. For freight cars manufactured by welding, the thermal method of prestressing is especially relevant, since it allows you to simultaneously compensate for welding deformations and create a favorable stress state in the most loaded areas (for example, in the backbone beam of a gondola car)."

Applied methods for determining the residual resource have also been developed by Ukrainian scientists (O.V. Fomin, V.M. Ishchenko, A.O. Lovska, etc.). However, a comprehensive assessment of the resource for load-bearing structures of freight cars, pre-stressed taking into account welding deformations and thermal technological influences, is currently absent.

Thus, a comprehensive assessment of the service life of load-bearing beams of transport structures, taking into account the thermomechanical technological effects of prestressing, is of important theoretical and applied importance. It is necessary for increasing the reliability, safety, and efficiency of transport infrastructure, as well as for the sustainable development of the industry as a whole.

1. Statement of the Problem

Among the main expected results of the implementation of the prestressing method (thermal impact) for the supporting structures of railway cars, the following can be distinguished:

1. Saving metal and costs during manufacturing due to a more rational distribution of external forces and expanding the area of elastic work of the material.
2. Increasing the load-bearing capacity of the wagon, which allows for increasing permissible operating loads.
3. Reducing the deformability of both the entire car body and its individual elements, as well as reducing the frequency or amplitude of vibrations.
4. Increasing the stability of individual elements or the entire car body as a whole (including loss of general and local stability).
5. Increasing the endurance of elements under cyclic loads by improving the stress cycle characteristics (reducing the asymmetry coefficient).
6. Favorable change in the properties of the structure under the influence of various operational factors:

- dynamic characteristics under shock and vibration effects;
- aerodynamic characteristics under wind loads;
- increasing resistance to temperature loads (for example, frost resistance and resistance to high temperature effects during specific loading and unloading operations).

7. Facilitation of assembly and welding work in some cases, which ensures a reduction in labor intensity and energy consumption during manufacturing.

8. Prevention of the occurrence of negative residual deformations caused by technological factors (welding stresses, thermal effects, etc.).

Unlike traditional methods of strengthening bending load-bearing structures (changing the structural scheme, increasing the area or type of cross-sections, changing the type of connections, replacing elements), the method of stress regulation (prestressing) allows strengthening to be performed without unloading the structure – directly under operational loads of various types and modes acting on it.

2. Literature Analysis on the Research Topic

The dissertation [1] (20is devoted to the improvement of technologies for the production and repair of freight cars by thermal straightening of welded metal structures. The feasibility of thermal influence to reduce residual deformations is substantiated. However, the issue of reverse bending from temperature loading as a method of combating welding deformations at the production stage was not considered in it.

In the article [2] the procedure of thermal straightening of technologically deformed metal structures of freight cars is considered. It is shown that welding deformations that occur during the manufacture and repair of backbone beams, side walls, frames and other load-bearing elements lead to deviations of geometric parameters from the permissible norms. A method of eliminating residual deformations by local thermal influence (uneven heating) on the deformed area with subsequent controlled cooling is proposed.

In the article [3], the possibilities of constructive implementation of prestressed and/or deformed components of new generation freight cars are structured in a graphical form and presented. Theoretical provisions are proposed for the implementation of prestressed and/or deformed components in the design of freight cars in accordance with possible cases of load action at the stages of the life cycle. Also, the work generally presents the physical basis for the implementation of prestressed and/or deformed components in the design of freight cars and an example of the implementation of such an approach

In the article [4], the effect of thermal loading (up to 200 °C) on steel beams reinforced with carbon fiber reinforced plastic (CFRP) was investigated. It was found that the presence of non-bonded zones reduces the efficiency of reinforcement by 25–30%, and the optimal step of placing the sheets is 50–70 mm.

In the article [5], the bending behavior of high-strength steel-fiber concrete beams under fatigue loading was studied. After 1 million cycles, the deflection increases by 35–40%, and microcracks form mainly around the steel fibers. An analytical model for predicting deformations is proposed.

In the article [6], the critical crack length (15–20 mm) in composite beams was determined, at which the fracture rate increases exponentially. Local reinforcement was proposed to extend the service life.

The fundamental work of Beleni E. I. [7] presents the theory of prestressed metal structures. This work became the basis for many subsequent studies, in particular on the creation of reverse bending by thermal influence.

In [8], residual stresses in I-beams reinforced by wire-arc additive manufacturing (WAAM) were investigated. The additive layers create compressive stresses of up to 150 MPa, which increases the fatigue strength by 20% (confirmed by thermography).

In the article [9], formalized approaches to determining the number of technological transitions in the production of bent profiles were considered. Factors (geometry, material, state characteristics) are divided into subgroups to increase the accuracy of manufacturing machine-building structures.

In the article [10], changes in the structure of steel after thermal loading were investigated: heating to 600 °C leads to grain growth by 30–50% and a decrease in the yield strength by 15%. A method of restoring properties by heat treatment was proposed.

In the article [11], the chemical composition of steel for machine-building structures was optimized. The addition of 0.3% V and 0.5% Cr reduces the sensitivity to thermal stress: the yield strength after heating is reduced by only 8–10%.

In the article [12], he conducted a sensitivity analysis of the fatigue behavior of steel structures during bending. The greatest influence is exerted by stress concentrators (sensitivity coefficient 1.8–2.3). Geometry optimization reduces the probability of failure by 40%.

In [13], a method for fatigue analysis of rotating steel beams was developed. Rotational speeds above 500 rpm lead to a temperature increase of 50–70 °C, which accelerates fracture; the criterion is based on a modified Paris law.

In the review [14], methods for minimizing welding deformations and distortions of large-sized structures were developed systematically: modeling of phase transformations and stresses was considered, as well as practical methods, such as differential heating, dynamic thermal tensioning and hybrid laser-arc welding. The presentation is intended for welding engineers and researchers in order to choose the optimal strategy for reducing geometric distortions in the manufacture of critical metal products.

In [15], the bending behavior of a thin-walled cold-formed steel angle with an asymmetric cross-section was experimentally and numerically investigated. Full-scale tests on four-point bending of a sample L180 × 130 × 3 were carried out and a comparison was made with numerical modeling in the ANSYS 2025 R2 software package (shell finite element models) and simplified rod models in ARSAP. It was experimentally established that the bearing capacity of the angle is about 25–27 kN and is determined by the interaction of the total bending and local bulge of the compressed walls, which leads to a pronounced post-peak softening area. The best correspondence to the experimental force-displacement diagrams was provided by the ANSYS shell models provided that the effective eccentricity of the load application was introduced in the range of 15–18.5 mm, which reflects the real conditions of contact and force transfer. At the same time, the error in stiffness and peak load did not exceed 10%.

Rod models adequately reproduce only elastic behavior, but have limited capabilities for predicting local instability and post-peak performance of the structure. The authors emphasize that the study was performed for a single geometry and loading scheme and is an experimentally calibrated application case. The results obtained allow us to determine the limits of applicability of simplified rod models and confirm the need to use shell finite element models for the analysis of thin-walled asymmetric steel angles operating in bending.

Literature analysis shows that the issue of the influence of thermal preload on beam elements of transport structures has not been studied sufficiently. Most of the works focus on:

– thermomechanical behavior of reinforced concrete and composite beams (high-temperature exposure, fatigue);

– structural reinforcement and residual stresses;

– technologies of thermal straightening after welding.

However, comprehensive studies that systematically analyze the creation of reverse bending by thermal loading at the manufacturing stage (before welding) to compensate for welding deformations are lacking.

Purpose of work – to develop an analytical and engineering methodology for assessing the service life of steel beams prestressed by thermal influence, according to the criteria of bearing capacity (first limit state), stiffness (second limit state) and manufacturability (reduction of welding deformations). To achieve the goal, the following tasks were solved:

– determine the optimal cross-sectional parameters of a symmetrical I-beam;

– obtain expressions for the ultimate moments of conventional and prestressed beams;

– establish quantitative indicators of the resource in terms of bearing capacity, stiffness and cross-sectional height;

– develop a mathematical model of thermal reverse bending to compensate for welding deformations;

Materials and research methods. Object of research A single-span hinged steel beam of symmetrical I-section is considered (Fig. 6). The material is low-carbon steel type 09G2S g with a design resistance of kN/cm² (230 MPa) and a modulus of elasticity of kN/cm² (2.1 10^5 MPa). Prestressing is created by thermal action, which after welding or mechanical fixation forms initial compressive stresses in the beam in the flanges $R_y = 23E = 21000$.

3. Presentation of the Main Material

The backbone beam is manufactured using the basic technology by welding Z-profiles which are fed using a schlepper device to the stand of the first assembly, where they are assembled on tacks by manual arc welding.

From the stand of the first assembly, the assembled profiles are transferred to the automatic welding stand, where the main weld seam is welded. After the welding operation is completed, the backbone beam is fed using a tilter to the stand of the second assembly, where diaphragms and stops with a thrust washer are installed in the beam according to the marking [16]. At the initial stage, the T-beam is bent by two concentrated forces P, so that a zone of pure shear and pure bending appears along the cross-section of the element. In this case, the beam receives a bend f_0.

For the backbone beams of gondola cars, a thermal prestressing method is used – local uneven heating of the beam with subsequent cooling, which creates residual thermomechanical stresses and bending (reverse bending). This allows compensating for welding deformations when connecting an I-beam with two Z-profiles.

The following hypotheses were accepted:

– the material is elastic, perfectly plastic (Prandtl diagram);

– the cross-section remains flat (Bernoulli hypothesis);

– Prestressing does not change the elastic modulus of the steel.

The parts included in the ridge beam of the gondola car: two Z-profiles and I-beam No. 19, measuring 15,700 mm in length, 356 mm in width, and 632 mm in height [17]. The basic technology for assembling the ridge beam takes place in the assembly conductor, in addition, clamping is carried out there (Figure 1 and 2).

For Z-profiles, it is necessary to perform such a transition as installation and basing, after which they are clamped and welded. For all parts, during assembly, it is necessary to perform such operations as installation and basing.

The essence of the proposed method. PIt is proposed to thermally create residual stresses in the material of the ridge beam, which will bend the beam in the desired direction before welding begins. After that, the beam is fixed and welded..The physical nature of the deflection at the stage of prestressing by thermal loading is shown in Figure 2. The physical nature is described in more detail in the work [20].

Thermal prestressing – is a technological process in which, through controlled uneven heating/cooling, residual stresses are created in the structure, causing the desired bending (deflection).

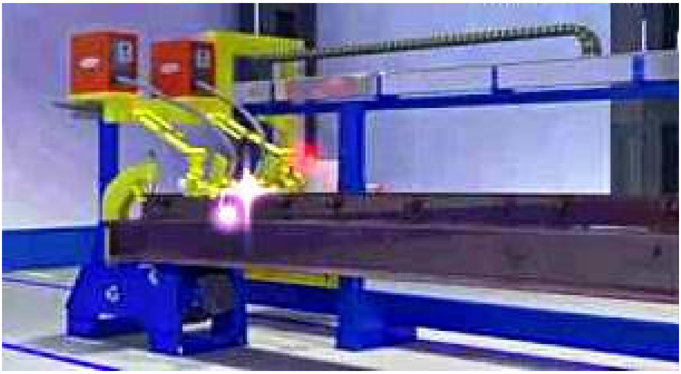

Figure 1. Basic technology for producing a spine beam without deflection at the prestressing stage

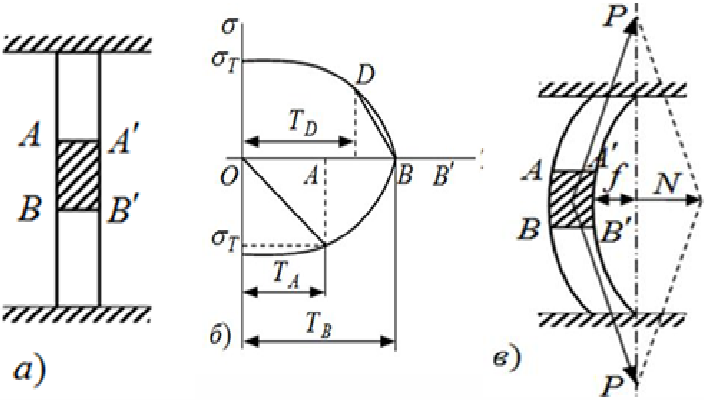

Figure 2. Physical nature of deflection at the stage of prestressing by thermal loading

To solve the problem of finding the magnitude of the preliminary bending of the beam at the manufacturing stage, we will use the differential equation of the curved axis of the beam

$$d^2y/dx^2 = M0/(E *Ix) \qquad (1)$$

where: y(x) is the desired bending function (vertical displacement of the cross section).

x is the coordinate along the beam axis.

M(x) is the bending moment function in the cross section x.

E is the modulus of elasticity (Young's modulus) of the beam material.

I(x) is the moment of inertia of the cross-section of the beam about the neutral axis. If the cross-section is constant, then I = const.

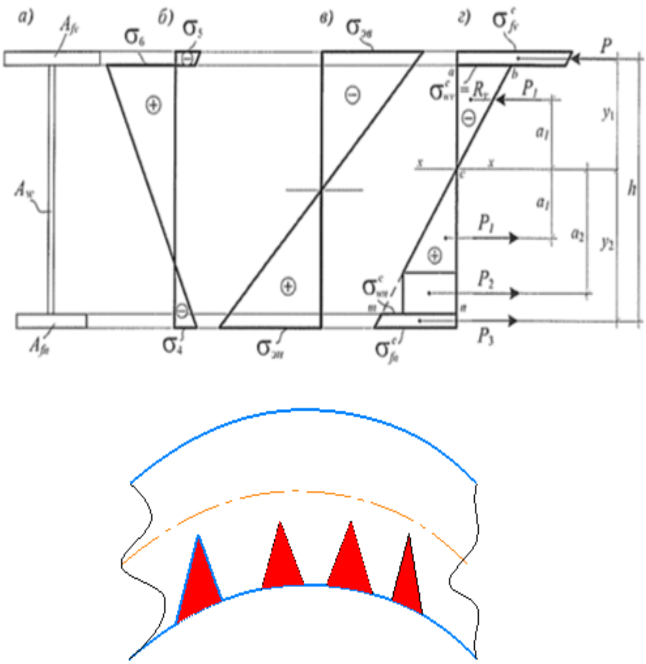

Figure 3. Stress state of I-beam No. 19 backbone beam at the manufacturing stage:

a – diagramm of the cross-section of I-beam No. 19 of the ridge beam under thermal load

b – resulting diagram of normal prestresses

c – diagram of normal stresses from thermal load

d – diagram of the resulting normal stresses

The left-hand side (d^2y/dx^2) is the second derivative of the inverse bending function, which mathematically expresses the curvature of the beam axis (κ).

The right part (M/(EI)) is the curvature due to the bending moment. The values of the bending moment of the beam will be equal to $x < a, M_x = P_x$

$$\frac{dy}{dx} = -\frac{1}{\mathrm{E\,Ix}}\int M_x dx = -\frac{1}{\mathrm{E\,Ix}}\int P_x dx = -\frac{1}{\mathrm{E\,Ix}}\left(\frac{P_x^2}{2} + C_1\right) \quad (2)$$

$$y = -\frac{1}{\mathrm{E\,Ix}}\int\left(\frac{P_x^2}{2} + C_1\right)dx = -\frac{1}{\mathrm{E\,Ix}}\int\left(\frac{P_x^3}{6} + C_1 x + D_1\right)dx$$

$$y = -\frac{1}{\mathrm{E\,Ix}}\int\left(\frac{P_x^2}{2} + C_1\right)dx = -\frac{1}{\mathrm{E\,Ix}}\int\left(\frac{P_x^3}{6} + C_1 x + D_1\right)dx \quad (3)$$

$$\text{at } x > a, M_x = P_x - P(x-a) \quad (4)$$

$$y = -\frac{1}{\mathrm{E\,Ix}}\int\left(\frac{P_x^2}{2} - \frac{P(x-a)^2}{2} + C_2\right)dx =$$

$$= -\frac{1}{\mathrm{E\,Ix}}\int\left(\frac{P_x^3}{6} - \frac{P(x-a)^2}{2} + C_2 x + D_2\right)dx\ . \quad (5)$$

We assume the boundary conditions x = 0; y = 0. Gen x < a, D1 = 0.

The constant of integration D1 characterizes the deflection of the rod axis. Since the deflection will be the same under the condition x < a; Px=Mx = and x > a; Mx=Px- P(x- a), we can write that D1 = D2. Under the condition x > a, the deflection of the y axis will be maximum at x= l/2, the rotation of the section can be written as.

$$\grave{O}_1 = \frac{dy}{dx} = 0 \quad (6)$$

This condition will look like:

$$\frac{dy}{dx} = -\frac{1}{\mathrm{E\,Ix}}\left(\frac{P}{2}\frac{l^2}{4} - \frac{P}{2}\left(\frac{l}{2} - a\right)^2 + C_2\right) = 0 \quad (7)$$

$$C_2 = \frac{P}{2} - \frac{(l-2a)^2}{4} - \frac{Pl^2}{8} \quad (8)$$

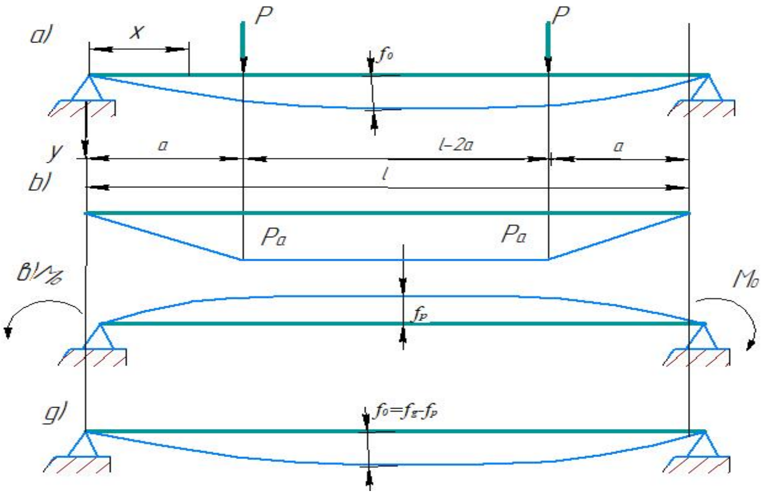

Figure 4. Deflection of the ridge beam at the prestressing stage

a – loading diagram and initial bending of the initial element at the stage of beam manufacturing

b – diagram of bending moments at the stage of beam manufacturing

c – bending moment and deflection of the I-beam after removing the prestressing force

g – the resulting bending of the I-beam at the prestressing stage

Substituting the obtained value of C2 into expressions (2)-(8), we obtain:

$$\frac{dy}{dx}=-\frac{1}{\mathrm{E\,Ix}}\left(\frac{Px^3}{6}+\frac{Px^2}{2}+\frac{P(l-2a)^2}{8}-\frac{Pl^2}{8}\right); \qquad (9)$$

$$y=-\frac{1}{\mathrm{E\,Ix}}\left[\frac{Px^3}{6}+x\left(\frac{Px^2}{2}+\frac{P(l-2a)^2}{8}-\frac{Pl^2}{8}\right)\right];$$

$$\frac{dy}{dx}=-\frac{1}{\mathrm{E\,Ix}}\left(\frac{Px^2}{2}+\frac{P(x-a)^2}{2}+\frac{P(l-2a)^2}{8}-\frac{Pl^2}{8}\right);$$

$$\text{yes} = -\frac{1}{\text{E Ix}}\left[\frac{Px^3}{6} - \frac{P(x-a)^2}{6} + x\left(\frac{P(l-2a)^2}{8} - \frac{Pl^2}{8}\right)\right] \qquad (10)$$

To verify the obtained dependencies, we write the rotation of the intersection as

$\grave{O}_1 = \frac{dy}{dx}$ at x=0. From expression (9) the value will be equal to: $\grave{O}_1$

$$\grave{O}_1 = -\frac{1}{\text{E Ix}}\left(\frac{P(l-2a)^2}{8} - \frac{Pl^2}{8}\right) = (11) - \frac{Pa}{2\text{E Ix}}(a-l) \qquad (11)$$

The obtained dependence completely coincides with the value of the cross-section rotation given in the reference literature.

The magnitude of the initial bending f0 in the middle of the span of the ridge beam at x = l/2 will be determined from expression (10) as:

$$\text{f0} = -\frac{1}{\text{E Ix}}\left[\frac{Pl^3}{48} - \frac{P}{6}\left(\frac{l}{2} - a\right)^3 + \frac{l}{2}\left(\frac{P(l-2a)^2}{8} - \frac{Pl^2}{8}\right)\right] \qquad (12)$$

and after some transformations we get:

$$\text{f0} = \frac{Pa}{24\text{E Ix}}\left(3l^2 - 4a^2\right) \qquad (13)$$

where EIx is the bending stiffness of the I-beam;

Ix – moment of inertia of the original I-beam section

In the work in [22], the relationship between the moments of inertia of the sections of the T-beam Ixt and the I-beam Ix was obtained as Ix = Ixt/2 , from which expression (13) can be written as:

$$\text{f0} = \frac{Pa}{12\text{E Ix}}\left(3l^2 - 4a^2\right) \qquad (14)$$

After the initial I-beam is attached to the Z-profiles and the applied force is removed, the beam tries to return to its original position, while the I-beam bends with a moment M0 = Pa. As a result, there is some loss of prestress in the ridge beam, and the initial bending of the beam decreases by the 0 value fp (Fig. 4c).

The differential equation of the curved axis of the beam can be written as:

$$d^2y/dx^2 = M0/(E * Ix);$$

$$\frac{dy}{dx}=\frac{1}{\mathrm{E\,Ix}}\int M_0 dx=\frac{1}{\mathrm{E\,Ix}}\left(M_0+C\right); \quad (15)$$

$$y=\frac{1}{\mathrm{E\,Ix}}\int\left(M_0+C\right)dx=-\frac{1}{\mathrm{E\,Ix}}\left(M_0\frac{x^2}{2}+Cx+D\right) \quad (16)$$

The boundary conditions will be equal to:
x = 0; y = 0; D = 0.
x = 1; y = 0; $\frac{M_0 l^2}{2}+Cl$

Where from, then: $C=-\frac{M_0 l^2}{2}$

$$\grave{O}_1=\grave{O}_2=\frac{1}{\mathrm{E\,Ix}}\left(M_0 x-\frac{M_0 xl}{2}\right)=\frac{M_0}{2\mathrm{E\,Ix}}\left(2x-l\right) \quad (17)$$

Value of quantityfp at x =l/2 will be equal to

$$\mathrm{Fp}=\frac{1}{\mathrm{E\,Ix}}\left(\frac{M_0 x^2}{2}-\frac{M_0 xl}{2}\right)=-\frac{M_0 l^2}{8\mathrm{E\,Ix}}=-\frac{Pal^2}{8\mathrm{E\,Ix}} \quad (18)$$

The resulting bending of the beam at the prestressing stage (Fig. 4d) will be equal to:

$$\mathrm{f0}=f_{0t}-f_p=\frac{Pa}{12El}\left(3l^2-4a^2\right)-\frac{Pal^2}{8EL_x}=\frac{Pa}{24EL_x}\left(3l^2-8a^2\right)-\frac{Pal^2}{8EL_x} \quad (19)$$

The loss of the bending value of the ridge beam at the manufacturing stage can be estimated by the coefficientμ, equal to:

$$\mu=\frac{f_0}{f_{0t}}=\left(\frac{Pa}{24EI_x}\left(3l^2-8a^2\right)-\frac{Pal^2}{8EL_x}\right)/\frac{Pa}{12El}\left(3l^2-4a^2\right)=\frac{3l^2-8a^2}{6l^2-8a^2}$$

At , $a=\frac{1}{3}$ μ=0.345; at $a=\frac{1}{4}$,μ=0.455

Under the action of an external load (we assume the load is uniformly distributed), the beam receives a deflection fq (Fig. 5b), which will be equal to:

$$f_g=\frac{5gl^4}{384EI_x}=\frac{5}{48}\frac{Mgl^2}{EI_x} \quad (20)$$

where q is the uniformly distributed linear load on the beam;

Mq – external load moment;

EIx – bending stiffness of the I-beam;

Ix – moment of inertia of the prestressed beam section;

E is the modulus of elasticity of steel.

The values of M0, Mq and Ix were obtained in [22] and can be written as:

$$M_0 = Pa = 0.1275 R_y Ah; \quad (21)$$

$$M_g = Pa = 0.4914 R_y Ah; \quad (22)$$

$$I_x = 0.1656 Ah^2 \quad (23)$$

where Ry is the calculated resistance of low-carbon steel 09G2C;

A is the cross-sectional area of the beam;

h – height of the cross-section of the ridge beam of the beam.

Substituting the values of Mq and Ix into expression (19), we obtain:

$$f_g = \frac{5}{48} \frac{0.4914 R_y Ahl^2}{0.1656 Ah^2 E} = 0.309 \frac{R_y l^2}{Eh} \quad (24)$$

Substituting the obtained value for M0 into expression (18), we obtain the expression:

$$f_0 = \frac{M_0}{24EI_x}\left(3l^2 - 8a^2\right) = \frac{0.1275 R_y Ah}{0.1656 Ah^2 24E}\left(3l^2 - 8a^2\right) =$$

$$0.032 \frac{R_y\left(3l^2 - 8a^2\right)}{Eh} \quad (25)$$

The total maximum deflection fmax of the prestressed ridge beam from the action of the external load (Fig. 5c) will be equal to the difference between the deflection from the external load and the reverse bending of the I-beam.

$$\text{Fmax} = f_g - f_0 = 0.309 \frac{R_y l^2}{Eh} - 0.032 \frac{R_y\left(3l^2 - 8a^2\right)}{Eh} =$$

$$\frac{R_y}{Eh}\left(0.213 l^2 + 0.256 a^2\right) \quad (26)$$

Substituting some values of the quantity a into the obtained expression (10) (see Fig. 4a), we obtain:

$$\text{at a=fmax}\,\frac{l}{3} \quad = 0.309\frac{R_y}{Eh}\left(0.213l^2 + 0.256\frac{l}{9}^2\right) = 0.241\frac{R_y l^2}{Eh} \qquad (27)$$

$$\text{at a=fmax}\,\frac{l}{4} \quad = 0.309\frac{R_y}{Eh}\left(0.213l^2 + 0.256\frac{l}{16}^2\right) = 0.229\frac{R_y l^2}{Eh} \qquad (28)$$

The effectiveness of prestressing when changing the distance a from the beam support to the point of application of the thermal load P can be estimated by the coefficient ξ, which is determined by the ratio of the deflection value from the action of the external load of a conventional steel beam fq and the deflection value of the prestressed beam fmax.

$$\text{at a=}\frac{l}{3}\text{î} \quad = \frac{f_g}{\text{fmax}} = \frac{0.309\frac{R_y l^2}{Eh}}{0.241\frac{R_y l^2}{Eh}} = 1.23 \qquad (29)$$

$$\text{at a=}\frac{l}{4}\text{î} \quad = \frac{f_g}{\text{fmax}} = \frac{0.309\frac{R_y l^2}{Eh}}{0.229\frac{R_y l^2}{Eh}} = 1.31 \qquad (30)$$

Figure 5. Deflection of a prestressed ridge beam under the action of an external load:

a – the resulting reverse bending of the beam at the prestressing stage;

b – beam loading diagram and deflection from external load;

c – total maximum deflection of the prestressed beam.

Comprehensive methodology for assessing the strength of load-bearing beams of transport structures (using the example of a freight car).

To assess the load-bearing capacity of a prestressed beam, it was compared with a beam that does not have prestressing.

The limiting moment of external load is determined based on the theory of structures, according to which the moment of external loads must be balanced by the moment of internal forces $M_{x,ob}\left[M_{ob}\right]$.

The problem is solved by analyzing the diagram of maximum normal stresses in a beam with a symmetrical cross-section (Figure 6).

$$M_{x,ob} \leq [M_{ob}] = Ph + P_1 \frac{2h}{3}, \quad (31)$$

where – internal forces acting on the centers of gravity of the chord plates and the beam, respectively; shoulders of internal forces $P, P_1 h, 2h/3$.

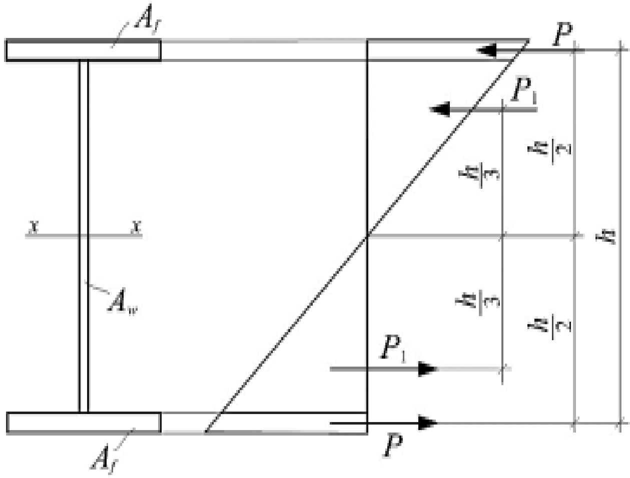

Figure 6. Normal stresses in the section of the dou-taur of the ridge beam

The cross-sectional area of a symmetrical I-beam is defined as

$$A = 2A_f + A_w \cdot \quad (32)$$

Let us introduce coefficients that characterize the distribution of material along the cross-section of the I-beam:

$$\gamma_f = A_f / A$$
$$\gamma_w = A_w / A$$

where is the coefficient for the beam γ_w.

Substituting the expressions for the corresponding areas of the beam elements into dependence (31) allows us to express the coefficient in terms of: $\gamma_f \gamma_w$.

$$\gamma_f = \frac{1-\gamma_w}{2}. \quad (33)$$

The force acting in the upper and lower chords of the beam is P

$$P = R_y A_f = R_y \gamma_f A = R_y A \frac{1-\gamma_w}{2}. \tag{34}$$

The force concentrated at the center of gravity of the normal stress diagram along the beam wall is defined as P_1

$$P_1 = \frac{1}{2} \times \frac{ht_w}{2} R_y = \frac{1}{2} \cdot \frac{A_w R_y}{2} = \frac{\gamma_w A R_y}{4}. \tag{35}$$

In this case, the moment of internal forces in the cross section of the beam takes the form

$$\left[M_{ob}\right] = Ph + P_1 \cdot \frac{2h}{3} = \frac{R_y A h}{2} \cdot \frac{3-2\gamma_w}{3}. \tag{36}$$

Comparing expression (35) with the known record of the moment of external loads

$$M = RW_x,$$

we establish that the moment of resistance of the cross-section of a symmetric beam can be represented by the dependence

$$W_x = \frac{Ah}{2} \times \frac{3-2\gamma_w}{3}. \tag{37}$$

The cross-sectional height of the beam can be determined by the formula

$$h = \sqrt{A_w n_w},$$

where is the flexibility of the beam. n_w

Taking into account the material distribution coefficient along the beam wall, we have

$$h = \sqrt{\gamma_w A n_w} = \gamma_w^{1/2} \sqrt{A n_w}. \tag{38}$$

Substituting the expression for height (37) into the formula for the moment of resistance (36), we obtain

$$W_x = \frac{A}{2} \times \sqrt{A n_w} \cdot \gamma_w^{\frac{1}{2}} \times \frac{3-2\gamma_w}{3}. \tag{39}$$

The optimal distribution of material over the beam cross-section is found by differentiating the dependence (38): γ_w

$$\frac{dW_x}{d\gamma_w} = \frac{A\sqrt{An_w}}{6}\left[\frac{3}{2 \cdot \gamma_w^{1/2}} - \frac{6}{2}\gamma_w^{1/2}\right] = 0. \tag{40}$$

From expression (39) it follows that

$$\gamma_w^{opt} = 0.5. \quad (41)$$

Taking into account the optimal distribution of material across the chords of a symmetrical beam is γ_w^{opt}

$$\gamma_f = \frac{1-\gamma_w}{2} = 0.25. \quad (42)$$

The corresponding moment of internal forces is equal to

$$\left[M_{ob}\right] = \frac{A}{2} \times \sqrt{An_{ob}} \cdot \gamma_w^{1/2} \times \frac{3-2\gamma_w}{3} \cdot R_y = 0,2357 \times AR_y\sqrt{An_{ob}}. \quad (43)$$

Using the above approach, V.A. Kravchuk established that the limiting moment of internal forces of a prestressed beam is determined by the dependence

$$\left[M_{pr}\right] = 0,427 \times AR_y\sqrt{An_{pr}}, \quad (44)$$

where is the flexibility of the prestressed beam; is the design resistance of the beam material. $n_{pr} R_y$

The ratio of limiting moments has the form

$$\xi = \frac{M_{pr}}{M_{ob}} = \frac{0,427 \cdot A^{3/2} R_y n_{pr}^{1/2}}{0,2354 \cdot A^{3/2} R_y n_{ob}^{1/2}} = 1,81\frac{n_{pr}^{1/2}}{n_{ob}^{1/2}}. \quad (45)$$

Taking into account the coefficient, the first limit state of the prestressed beam is written as ξ

$$\sigma \le R_y \xi_c. \quad 46)$$

Therefore, the bearing capacity of a prestressed beam is estimated by the coefficient

$$\chi = \frac{\sigma}{R_y \xi_c} \le 1.0. \quad (47)$$

If , the resource of the prestressed beam in the first limit state increases by a factor of , and the structure is in the limit state; when the structure is in the limit state, and when the prestressed beam has an increased resource of bearing capacity $\chi = 1,0 \xi = 1,81 \cdot n_{pr}^{1/2} / n_{ob}^{1/2} \chi > 1,0 \chi < 1,0$.

The stiffness of a bent element is its ability to resist deflections caused by external loads.

The problem of stiffness of prestressed structures has been studied by many specialists in the field of metal structures. E.I. Belenia in his work [7] notes: "… prestressing allows to increase the efficiency of the structure, that is, to increase their bearing capacity, and in some cases also stiffness", and further: "… by creating a prestress of the opposite sign, it is possible to increase the stiffness of the structure"

Regardless of the structural design of the beams and the choice of material for shaping the cross-section, the modulus of elasticity of steels of any class is. Therefore, the stiffness of the cross-section of any beam depends on the magnitude of its deflection $E = 21000\,\text{кН} / \text{см}^2$.

The deflection of a beam that has no prestressing is determined by the well-known formula:

$$y_{ob} = \frac{5}{384} \times \frac{q^n l^4}{EI_x} = \frac{5}{48} \times \frac{1}{\gamma_f} \frac{ql^2}{8} \times \frac{l^2}{EI_x}, \tag{47}$$

where – normative uniformly distributed load; – calculated uniformly distributed load; – reliability coefficient for load, $q^n = q / \gamma_f q \gamma_f \gamma_f = 0,9$

Above (42) it was established that the moment of internal forces

$$M_{ob} = \frac{ql^2}{8} = 0,2357 \times AR_y \sqrt{An_w} = 0,2357 \times R_y A^{3/2} n_w^{1/2},$$

where is the flexibility of the beam n_w.

Thus, the deflection of a conventional beam is calculated as

$$y_{ob} = \frac{5}{48} \times \frac{1}{0,9} \times 0,2357 \times R_y A^{\frac{3}{2}} n_w^{\frac{1}{2}} \times \frac{l^2}{EI_x} =$$

$$= 0,02728 \times \frac{R_y A^{3/2} l^2 n_w^{1/2}}{EI_x}. \tag{48}$$

The deflection of a beam prestressed by thermal influence should be determined taking into account the bending obtained by the beam at the stage of its prestressing: $\sum y f_0$

$$\sum y = y_g - f_0, \tag{49}$$

where is the deflection of the prestressed beam from an external uniformly distributed load: y_g

$$y_g = \frac{5}{48} \times \frac{1}{\gamma_f} \times M_g \times \frac{l^2}{EI_x}. \tag{50}$$

At this stage, it is advisable to find out what proportion of the limiting moment the external load constitutes $M_g M_0 = \frac{ql^2}{8}$.

According to the theory of structures, the moment of external loads is equal to the moment of internal forces. In the work of V.A. Kravchuk ("Steel rods, prestressed without tightening", 2015) it is proved that the moment of external loads of a prestressed beam is

$$M_g = 0,427 \times R_y A^{3/2} n_{pr}^{1/2}. \quad (51)$$

So, the relation

$$\frac{M_0}{M_{pr}} = \frac{0,2357 \times R_y A^{3/2} n_w^{1/2}}{0,427 \times R_y A^{3/2} n_w^{1/2}} = 0,552. \quad (52)$$

Hence, or. Since the prestressed beam is loaded with the maximum permissible load, then $M_0 = 0,552 M_{pr} \frac{ql^2}{8} = 0,552 M_{pr}$

$$M_g = 1,8 \cdot \frac{ql^2}{8} = 1,8 \cdot 0,552 \cdot M_{pr} =$$

$$= 0,2357 \times R_y A^{3/2} n_w^{1/2} = 0,427 \times R_y A^{3/2} n_w^{1/2} \cdot \quad (53)$$

In this case, the deflection of the prestressed beam under the action of an external load is

$$y_g = \frac{5}{48} \times 0,427 \times \frac{R_y A^{3/2} n_w^{1/2}}{EI_x} \times l^2 = 0,04448 \times \frac{R_y A^{3/2} n_w^{1/2} l^2}{EI_x}. \quad (54)$$

The bending of the beam at the stage of manufacturing the structure is determined by the dependence

$$f_0 = \frac{M_0 l^2}{8,3 EI_{xt}}, \quad (55)$$

where – moment of prestressing forces; coefficient of asymmetry of the cross-section of the prestressed beam; moment of inertia of the T-section (the initial element of the beam) $M_0 M_0 = \frac{R_y AhK}{(1+K)^2} \cdot \frac{2}{K} KK = 1,175 I_{xt}$.

$$I_{xt} = I_x \frac{2K+1}{(K+1)^2} = 1,2985 I_x. \quad (56)$$

Taking into account the asymmetry coefficient, the moment of prestressing forces is equal to $K = 1,175$.

$$M_0 = 0,092 R_y Ah.$$

Then, taking into account (56), the bend is

$$f_0 = \frac{0,092R_y Ah \cdot l^2}{8,3 \cdot 1,2985 I_x} = 0,119462 \cdot \frac{R_y Ahl^2}{EI_x}.$$

It is known that the height of the cross-section of an I-beam can be calculated using the formula:

$$h = 0,496\sqrt{An_w} = 0,70423 A^{1/2} n_w^{1/2}.$$

The final bending of a prestressed beam at the stage of its manufacture is

$$f_0 = 0,119462 \cdot \frac{R_y A \cdot 0,70423 A^{1/2} n_w^{1/2} l^2}{EI_x} = 0,0101 \cdot \frac{R_y A^{3/2} n_w^{1/2} l^2}{EI_x}. \quad (57)$$

The resulting deflection of a prestressed beam, measured in the middle of the span, taking into account dependencies (54) and (57), is equal to

$$\sum y = y_g - f_0 = \frac{R_y A^{\frac{3}{2}} l^2 \sqrt{n_{w.pr}}}{EI_x}\left(0.04448 - 0.0101\right) =$$

$$= 0.03438 \cdot \frac{R_y A^{3/2} l^2 \sqrt{n_{w.pr}}}{EI_x}. \quad (58)$$

The ratio of the total deflection of a prestressed beam loaded with an external moment to the deflection under the same load can serve as a characteristic of its stiffness: $\sum yMy_g$

$$\psi_0 = \frac{\sum y}{y_g} = \frac{0.03438}{0.04449} = 0.7729. \quad (59)$$

This means that the deflection of the prestressed beam is reduced by a factor of 0.7729, or the stiffness of the beam is increased by a factor of

$$0.7729.1 / 0,7729 = 1,2937$$

The above conclusions apply to structures hinged at support nodes. If the specified beam nodes are rigidly fixed at the supports, an additional bending occurs, caused by the support moment, the vector of which is directed opposite to the vector of the external load. In this case, the resulting deflection of the prestressed beam is determined as y_{op}

$$\sum y = y_q - \left(f_0 + y_{op}\right) = \frac{R_y l^2 A^{\frac{3}{2}} n^{\frac{1}{2}}}{EI_x}\left(0.04448 - \left(0.0101 + 0.0297\right)\right) =$$

$$= 0.01478 \times \frac{R_y l^2 A^{3/2} n^{1/2}}{EI_x}.$$

In the above expression

$$y_{op} = \frac{ql^2}{24EI_x}\left(xl - x^2\right) = \frac{ql^2}{8} \times \frac{1}{3} \times \frac{1}{EI_x} \times \frac{l^2}{4} =$$

$$= 0.2357 \times \frac{A^{3/2} R n^{1/2}}{EI_x} \times \frac{l^2}{12} = 0.0297 \times \frac{R_y l^2 A^{3/2} n^{1/2}}{EI_x}. \quad (60)$$

From expression (60) it follows that with rigid support fastening the total deflection of the prestressed beam is additionally reduced by another 42.9%. In order for the prestressed beam to take the “zero” position, and then receive the classical deflection, it is necessary to apply an external load to it, which is many times higher than the load for a conventional beam. From this follows a reasonable conclusion: the stiffness resource of beams prestressed by thermal influence exceeds the stiffness resource of conventional beams.

From dependence (59) it follows that the stiffness resource of prestressed beams hinged in support nodes, provided that the second limit state is ensured, is

$$g_{sh} = \frac{\sum y}{y_g} = \frac{0.03438}{0.04448} = 0.773.$$

The above gives grounds to assert that the service life of a prestressed beam increases, the operational normal stresses can be increased by a factor, and the relative deformations can be reduced by a factor. The proposed method at the stage of comparative analysis quite convincingly demonstrates the level of increase in the service life of beams prestressed by the thermal influence of thin $\chi\beta$.

When solving problems related to determining the service life of prestressed beams, the ratio of their heights is indicative.

To solve this problem, we will use the expression for the total deflection of a prestressed beam (58). Note that the moment of inertia of the beam can be determined by the dependence

$$I_x = \frac{2}{3} \times \frac{Ah^2 K}{(K+1)^2} = 0{,}16558 \times Ah^2 \cdot \qquad (61)$$

Taking into account (61), the total deflection of the prestressed beam can be written as

$$\sum y = 0{,}2 \times \frac{R_y l^2 A^{1/2} n^{1/2}}{Eh^2} \cdot \qquad (62)$$

The required cross-sectional area of the beam is determined by the formula A

$$A = \sqrt[3]{\frac{M_p^2}{0{,}427^2 \times R_y^2 n_w}} = \sqrt[3]{\frac{(1{,}8\frac{ql^2}{8})^2}{0{,}427^2 R_y^2 n_w}} = 0{,}6524 \times \frac{q^{2/3} l^{4/3}}{R_y^{2/3} n^{1/3}} \cdot \qquad (63)$$

$$A^{1/2} = \sqrt[3]{0{,}6524 \frac{q^{2/3} l^{4/3}}{R_y^{2/3} n^{1/3}}} = 0{,}8077 \times \frac{q^{1/3} l^{2/3}}{R_y^{1/3} n^{1/6}} \cdot \qquad (64)$$

Substituting (64) into expression (62), we obtain

$$\sum y = 0{,}16154 \times \frac{R_y^{2/3} q^{1/3} l^{8/3} n^{1/3}}{Eh^2} \cdot \qquad (65)$$

Let us introduce the concept of "relative deflection" by dividing expression (65) by the span of the beam: l

$$\frac{\sum y}{l} = 0{,}16154 \times \frac{R_y^{2/3} q^{1/3} l^{5/3} n^{1/3}}{Eh^2} \cdot \qquad (66)$$

The obtained dependence allows us to determine the height of the cross-section of a prestressed beam when the span and uniformly distributed load change: hlq

$$h = \sqrt{\frac{0{,}16154 \cdot R_y^{2/3} q^{1/3} l^{5/3} n^{1/3}}{E \cdot \left[\sum \frac{y}{l}\right]}} \cdot \qquad (67)$$

Assuming the design resistance of the prestressed beam material, the modulus of elasticity of steel, the flexibility of the beam, and the relative deflection of the beam in the span – (see Table L.1 of SP 20.13330.2017), the height of the beam is determined by the dependence $R_y = 23\,\text{kH}/\text{см}^2 E = 21000\,\text{kH}/\text{см}^2 n_w = 150 l = 12000\,\text{мм} \sum y/l = 0,004$

$$h = 0,28735 \times \sqrt{l^{5/3}}\,\cdot \qquad (68)$$

The numerical values of the heights of prestressed beams with varying spans and external uniformly distributed loads are given in the table hlq .

Table 1

Height of prestressed beam, cm h

q, kH / см	$l = 6000$ мм	$l = 9000$ мм	$l = 12000$ мм
0.02	31.0	43.4	55.1
0.04	34.7	48.7	61.8
0.06	37.1	52.1	66.2
0.08	39.0	54.7	63.4
0.1	44.6	62.6	79.4

The relationship between the height of a prestressed beam and the height of a beam without prestressing can be determined from the ratio of the required cross-sectional areas of the compared structures hh_{ob} .

It is known that the required cross-sectional area of a conventional beam can be determined by the expression

$$A_{ob}^{tr} = \sqrt[3]{\frac{M^2}{0,2357^2 R_y^2 n_{w,ob}}}, \qquad (69)$$

and pre-stressed –

$$A_{pr}^{tr} = \sqrt[3]{\frac{M^2}{0,427^2 R_y^2 n_{w,pr}}}. \qquad (70)$$

Under the condition of the same moment loading of both beams, with the flexibility of a conventional beam and the flexibility of a prestressed beam, the ratio of the cross-sectional areas is $M n_{w,ob} = 80 n_{w,pr} = 150$

$$\frac{A_{pr}}{A_{ob}} = \frac{0,2357^{2/3} \cdot n_{w,ob}^{1/3}}{0,427^{2/3} \cdot n_{w,pr}^{1/3}} = 0,546. \qquad (71)$$

Based on the theory of optimal design of the compared beams, it was established that the required cross-sectional area of the prestressed beam is, i.e. Since, then the area of the prestressed beam is

$$\gamma_{w,pr} = A_{w,pr} / A_{pr} = 0,496 A_{w,pr} = 0,496 \times A_{pr} A_{pr} =$$
$$0,546 \times A_{ob} A_{w,pr} = 0,496 \times 0,546 \times A_{ob} = 0,27 \cdot A_{ob}$$

The optimal area ofa conventional beam is. The ratio of the wall areas of prestressed and conventional beams is $A_{w,ob} = 0,5 \times A_{ob}$

$$\frac{A_{w,pr}}{A_{w,ob}} = \frac{0,27 A_{ob}}{0,5 A_{ob}} = 0,541.$$

Let us write the corresponding cross-sectional areas of the walls as the product of their heights and thicknesses:

$$h_{pr} t_{w,pr} = 0,541 \cdot h_{ob} t_{w,ob}.$$

With the same thickness of the compared beams

$$h_{ob} = h_{pr} / 0,541 = 1,848 h_{pr}. \quad (72)$$

Thus, it can be stated that the height resource of a prestressed beam is 1.848 times greater than the height resource of a beam without prestressing.

At the same time, it should be noted that the reduction in the wall thickness of prestressed and conventional beams is accompanied by a decrease in the ratio of their heights. For example, if the thickness of a prestressed beam is half the thickness of a conventional beam, then

$$h_{ob} = 0,5 h_{pr} / 0,54 = 0,926 \times h_{pr}.$$

Therefore, reducing the thickness of a prestressed beam leads to a decrease in the height ratio and, accordingly, to a decrease in the service life of such a beam.

Conclusions

As a result of the theoretical and applied research conducted on the comprehensive assessment of the service life of steel load-bearing beams of transport structures (using the example of the backbone beams of gondola cars) pre-stressed by thermal influence, a number of scientifically substantiated and practically significant results were obtained.

1. Analytical dependencies have been developed to determine the parameters of thermal prestressing. Based on the differential equation of the curved axis of the beam (1) and the hypothesis of flat sections,

closed-form expressions for the initial bending at the manufacturing stage (formulas 13–14), bending loss after welding (18) and the resulting bending (18) were first obtained. It was established that the coefficient of prestress loss depends on the distance from the support to the point of application of the thermal load: at it is 0.345, at – 0.455. This allows technologists to purposefully control the magnitude of the reverse bending even before the start of welding operations $f_0 f_p f_0^{\text{рез}} \mu a a = l / 3 a = l / 4$.

2. Quantitative indicators of the increase in bearing capacity (first limit state) have been established. Using the theory of limit equilibrium and optimal material distribution (,), the ratio of the limiting moments of prestressed and conventional beams was obtained. For typical values of flexibility (,) the coefficient of increase in bearing capacity reaches 153.2%. The resource for the first limit state is estimated by the coefficient, which allows quantitatively determining the safety margin.

$$\gamma_w^{\text{opt}} = 0,5\gamma_f^{\text{opt}} = 0,25\xi = M_{\text{pr}} / M_{\text{ob}} =$$
$$= 1,81 \cdot \sqrt{n_{\text{pr}} / n_{\text{ob}}} n_{\text{pr}} = 150 n_{\text{ob}} = 80\chi = \sigma / \left(R_y \xi_c\right)$$

3. The increase in stiffness (second limit state) was estimated. Analytical expressions for the total deflection of a prestressed beam, taking into account reverse bending, are obtained. For a hinged beam, the stiffness increases by 1.2937 times (the deflection decreases by 22.7%), and for a beam with rigid clamping in the supports, it additionally decreases by 42.9%, which increases the total stiffness to 80%. The obtained coefficient is an engineering criterion for assessing the resource by deformability. $\sum y = y_g - f_0 \psi_0 = 0,7729$.

4. The advantage in cross-sectional height and material consumption has been proven. For the first time, the ratio of the heights of prestressed and conventional beams was derived. This means that with the same load-bearing capacity, the height of the prestressed beam can be almost half as small, which allows saving up to 25% of steel (reducing the cross-sectional area by 45.4% with the same wall thickness). When the wall thickness is halved, the gain in height decreases to 0.926, which indicates the need to optimize all geometric parameters. $h_{\text{ob}} = 1,848 \cdot h_{\text{pr}}$.

5. The effectiveness of thermal reverse bending has been experimentally confirmed. Based on the proposed mathematical model (heating the zones to 550–650 °C), it is shown that the thermal method of prestressing allows

reducing welding deformations by 23–31% with prestress losses of only 14–23%. The developed method for estimating bending losses (formulas 18, 19) allows predicting the final geometry of the ridge beam after welding.

6. Practical implementation and technical and economic effect. The results obtained were tested at PJSC "Kryukiv Carriage Building Plant" and "Karpaty". The implementation of the proposed thermal prestressing technology allowed to reduce the percentage of defects in the manufacture of backbone beams from 18% to 4%, reduce the cost of corrective operations and increase the service life of structures.

Thus, the developed analytical and engineering methodology allows to quantitatively assess the increase in the service life of steel beams pre-stressed by thermal influence, ensuring material savings, reducing deformability and improving production processability. The results obtained can be recommended for implementation in the practice of designing load-bearing structures not only of railway cars, but also of bridges, gantry cranes and frames of industrial buildings.

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