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Determination of limit load bearing capacity of rod metal structures

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Abstract
This article presents results of numerical simulation of spatial rod metal structures, allowing, in contrast to traditional method of calculation, based on identification of most stressed structural elements, determination of a limit on load bearing capacity of an entire structure as a whole, allowing formation of plastic deformations in these elements, which can significantly increase operational loads. Modern computing systems based on finite element method and the possibility to perform incremental calculations based on geometrical and physical nonlinearity of deformation of the structure and properties of the materials from which it is made of, can effectively identify the potential for increasing the load bearing capacity of the structure under the assumption of possible appearance of small plastic deformations in the some elements. The proposed new approach to the calculation of load bearing capacity limit for metal structures, taking into account the current capabilities of computer software systems, makes it possible to get away from the piecemeal methods of testing the strength, rigidity and stability of building structures and consider the whole structure as a single system. This approach was successfully used when checking the load bearing capacity of covering of Ice Palace three arenas, which was built in Moscow in 2015 in the former ZIL car factory.

Keywords: method, modeling, calculation, carrying capacity, rod metal structure, elastic, plastic strain, stress.

Modern security requirements for unique and heavy-duty buildings of sports, entertainment, cultural and shopping destination [1, 2] dictate the need to apply when designing the most advanced computational methods in order to objectively evaluate performance of these building structures during construction and operation [3].
Performance analysis of complicated spatial rod structures, such as large-span covering a heavy-duty buildings, should be carried out for the whole constructive complex, taking into account the geometric and physical nonlinearity [4], that would allow you to more objectively evaluate the stress-strain state (SSS) both for the entire structure and its the most loaded individual elements.
For current domestic [4, 5] and foreign [6] calculation regulations of rod metal structures based on concept of load bearing capacity checking of the most loaded structural elements, which is an involuntary consequence of traditional notion of immutability of geometric constructions scheme during loading.
In particular, verification of load bearing capacity for compressed rod structural elements takes into account possibility of loss of stability and is based on the expression:

$$N \le N_c \qquad (1)$$

$$N_c = R \cdot A \cdot \varphi \qquad (2)$$

where
N – calculated force in the rod;
N_C – load bearing capacity of structural element;
A – geometrical parameter of section – the cross-sectional area in the case of compression / tension, the moment of resistance in case of bending;
R – calculated resistance of the structural element's material ;
φ – stability coefficient ($\varphi \le 1$), which is the ratio of the critical stress σ_{cr} to the calculated resistance R.
Thus, calculated in accordance with expression (2) limit load bearing capacity N_C of single element corresponds to the achievement of critical stress not exceeding yield strength $\sigma_{cr} \le \sigma_{\text{T}}$. However, actually, the yield point achievement in one element at a level of plastic strain of about 3% (the so-called small elastic-plastic deformation) does not mean further development of buckling therein or fracture and leads to a redistribution of forces on neighboring elements and subsequent growth of stresses in these elements, where flow element reached the limit, continues to stay workable as the load may keep growing. The load bearing capacity of the overall structure, respectively, also increases.
Modern computing systems based on finite element method and the possibility to perform incremental calculations based on geometrical and physical nonlinearity of deformation of

the structure and properties of the materials from which it is made of [7, 8], can effectively identify the potential for increasing the load bearing capacity of the structure under the assumption of possible appearance of small plastic deformations in the some elements.

During a step by step calculation on each step of loading the actual design of construction scheme and of state of the structural elements material are automatically adjusted, thus eliminating the need to address the required regulatory documents for such important events as the loss of general or local stability of structures or some of its elements. Question of specific cause of load bearing capacity exhaustion fades into the background – this may be the loss of general or local stability, element's strength, and so on.

Thus it is possible to calculate the ultimate load bearing capacity of the structure as a whole and to compare its corresponding external loads with a full load imposed on the basis of existing rules [9].

In [10] it is shown that under such approach criterion of limit load bearing capacity of the construction can be a critical external load $\vec{P}_{cr}$, at which the intensity of the development of plastic deformation in the most deformed elements and the maximum displacement of the characteristic points (nodes) of structure begin to grow without noticeable growth of the external load. Here the components of the vector $\vec{P}$ are different types of loads (dead weight, wind, snow, etc.). It is important that the value of $\vec{P}_{cr}$can significantly exceed the calculated regulatory process design load $\vec{P}$ (Fig.1).

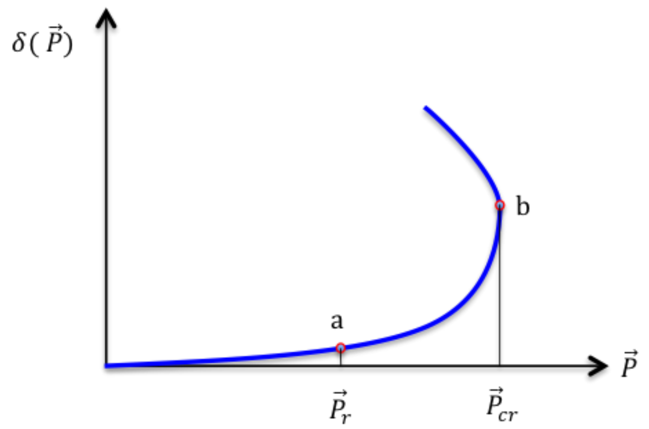

Fig. 1 - The dependence of the nodal displacements from the external load.

Theoretically, on this curve there is a point b, where the derivative $\frac{d\delta}{dP} \to \infty$. This point corresponds to the limit load bearing capacity of the whole structure $\vec{P}_{cr}$. At the point b the criterion of Lyapunov stability loss – when a small increment of the argument $\overrightarrow{\Delta P}$ corresponds to a disproportionate increase in the function Δδ [11, 12]. Part of the curve above the stage b is structural failure when the strain continued to grow in the condition of declining external load.

This approach is effective not only for the rod structures (trusses, frames, three-dimensional rod structures), but also for the multi-complex constructions consisting of shell, volumetric and structural elements of another type with different physical and mechanical characteristics and properties [10].

The ratio of ultimate load bearing capacity of the structure $\vec{P}_{cr}$ to the estimated load $\vec{P}_r$ is a general safety factor γ for the entire structure:

$$\gamma = \frac{\vec{P}_{cr}}{\vec{P}_r} \geq [\gamma] \qquad (5)$$

This ratio characterizes the supply of the load bearing capacity of the structure respectively to those calculated in accordance with the existing rules of loads and must also be normalized. In the absence of relevant documents its minimum value of [γ] should be set by the design assignment or special technical specifications (STS).

Nonlinear analysis held in this way provides information about the stress-strain state of structural elements. The criterion of performance of the first limit state of load bearing capacity for the rod elements is the following expression:

$$\gamma_n \cdot \frac{\sigma_{max}}{R_y \cdot \gamma_c} \leq 1;$$
$$\gamma_n \cdot \frac{\tau_{max}}{R_s \cdot \gamma_c} \leq 1 \qquad (6)$$

where σ_{max} , τ_{max}– maximum normal and tangential stresses in the elements due to unfavorable combination of design loads;

R_y, R_s – calculated resistance of the material, respectively, the normal and tangential yield strength;

γ_n, γ_c – safety factor for responsibility and working conditions factor.

These considerations for rod metal structures can be applied to the base metal structural elements, but it is clear that a similar approach should be applied to the evaluation of the strength of nodal connections (welded and bolted), which should be properly modeled and taken into account in finite element analysis [13].

For flat, shell and volumetric structural elements given the maximum von Mises stress on $\sigma_{\text{пр}_{max}}$ should not exceed the design strength with appropriate safety factors [14]. For the elements working in the conditions of plane stress state (PSS), the expression is:

$$\sigma_{\text{пр}_{max}} = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x \cdot \sigma_y + 3\tau_{xy}{}^2} \leq \frac{R_y}{\gamma_n} \cdot \gamma_c \qquad (7)$$

In the local stress concentration zones, in which significant plastic deformation may appear, it is also necessary to satisfy their values to 3% criterion of small elastic-plastic deformations, expresses by the limitation of the maximum value of the reduced strain $\varepsilon_{\text{пр}_{max}}$, when the PSS calculated as follows:

$$\varepsilon_{\text{пр}_{max}} = \frac{2}{3}\cdot\sqrt{\varepsilon_x^2+\varepsilon_y^2-\varepsilon_x\cdot\varepsilon_y+\frac{3}{4}{\gamma_{xy}}^2} \leq 3\% \quad (8)$$

Also, a checking must be made on the second limit state for the limitation to the largest displacements from the regulatory load:

$$\gamma_n \cdot \delta \leq \Delta \quad (9)$$

where

δ – largest displacement of structure from the regulatory load;

Δ – limit value of the corresponding displacement, determining the capability of the normal structure operation [9].

Experience of the application of such methodology for the calculation of steel structures [10] shows that the minimum value of the safety factor, calculated by the formula (5), [γ] = 1.6 gives satisfactory results. In most practical cases, the value of [γ] can greatly exceed this value while maintaining uniform strength of the base metal and junctions.

The presented procedure was used when checking the load bearing capacityof covering of Ice Palace three arenas, which was built in Moscow in 2015 in the former ZIL car factory.

Coating system of supporting structures consist of the main cross-carrying trusses of 80 m span spatially combined with the neighboring farms with the help of a sufficiently dense system of longitudinal, transverse, horizontal, vertical and oblique connections. Thus, the carrying structures of coating system substantially generates a multi-element spatial lattice plate (similar spatial rod structures), which is supported by the interaction of all components comprising the coating of the large arena, consisting of two substantially similar sections separated by an expansion gap (photo.1).

Photo.1. General view of the covering carrying structures of the large arena.

During the engineering survey conducted with the help of a specially developed technology [15] for accessing general quality of the construction of the buildings, it was found that the carrier design of the coatings in the construction have been mounted with a number of deviations from the design position, reaching up to 12 cm.

The numerical modeling of the coating executed in this survey solves two main tasks:

- establish how the identified deviations affect the load bearing capacity of covering supporting structures calculated in accordance with regulatory documents;
- estimate the actual load bearing capacity of the coating according the above procedure with the possibility of formation of small elastic-plastic deformation (<3%) in the structural elements.

Preliminary calculations carried out in accordance with the regulatory requirements of the action of the design loads for the design geometry coverage, and taking into account the identified deviations [16], set the position of the most loaded structural elements (Figure 2), which upon further increase in load conditions will develop plastic deformation in simple loading condition [17].

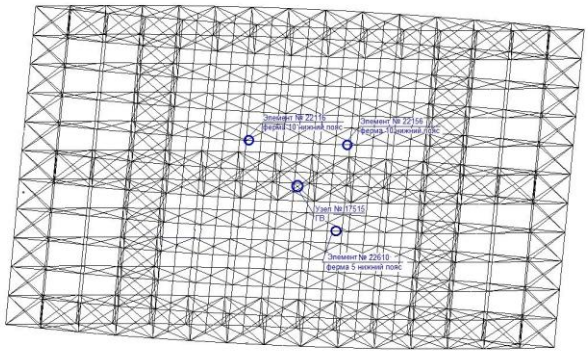

Fig.2. Numerical model of a covering section of the large arena with the disposition of the most loaded elements according this the result of regulatory analysis.

A quite well working for the majority of structural metal within the small elastic deformations at the nonlinear formulation bilinear stress-strain diagram of steel with linear hardening zone was used during the numerical calculations of the coating load bearing capacity of metal constructions is presented at Figure 3.

Construction material – steel C345, modulus of elasticity E=2,1·10^5 MPa, hardening modulus E_t =2·10^3 MPa, tensile strength Ry=310 MPa, Poisson ratio ν=0.3.

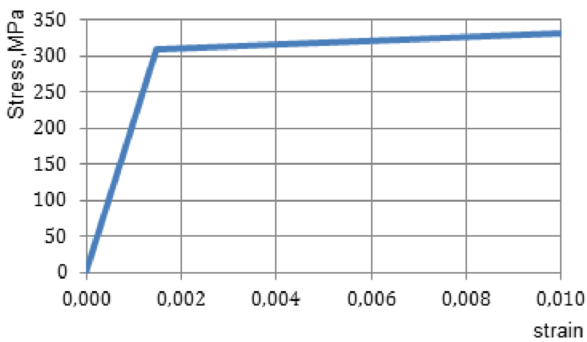

Fig. 3. The bilinear stress-strain diagram of steel C345.

The calculation for the base metal roof trusses of covering was performed in the finite element analysis system NASTRAN in geometrically and physically nonlinear formulation at step by step procedure. The following is a typical plot of strains in one of the most loaded elements – in the middle lower panel of one of the truss (№10). The value of the abscissa, equal to one, corresponds to the design load *Pr*, determined in accordance with the regulations (Figure 4).

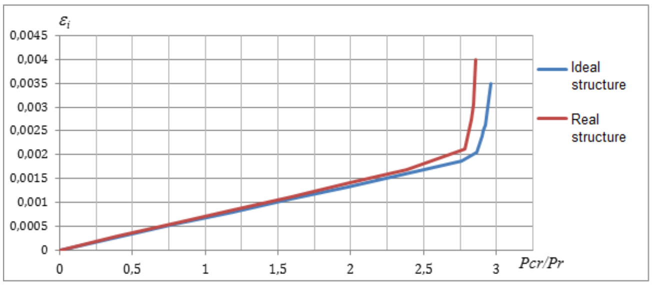

Fig. 4. The intensity of deformation in the middle lower panel of the truss 10.

The graph shows that the continuation of simple loading above the value of *Pr* retains substantially linear nature of the deformation up to values of *Pcr/Pr*=2,6÷2,7, meaning that the base metal of the structure has a substantial margin of load bearing capacity corresponding to obtained relationship.

The graph also shows that the initial assembly imperfections made during mounting of the structure has a marked negative impact on the load bearing capacity that reduces critical loads value to 5% when the level of the geometric assembly imperfections is about of 0,15%.

This work confirmed in practice at a real object the main provisions of [10], proving that metal structures projected under the existing regulations in fact have significant undetected and untapped reserves of strength.

The proposed new approach to the calculation of limit load bearing capacity for metal structures, taking into account the current capabilities of computer software systems, makes it possible to get away from the piecemeal methods of testing the strength, rigidity and stability of building structures and consider the whole structure as a single system.

Of course, this approach can only be applied under conditions ensuring the desired quality of prefabricated structures and junctions, as well as their assembly during installation.

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