1. Introduction

One of the ways of increasing the efficiency of building production is the transition to the use of light metal structures in the most large-scale areas of civil engineering – construction of industrial, public buildings and structures for various purposes.

New design shapes of light metal structures should inherit the best quality of the traditional systems and encourage the use of advanced profiles, high-strength steel grades, light alloys, etc. At the same time they should allow carrying out easily enough the artificial regulation of effort and stress, having simple nodal pairing, being technologically advanced in manufacturing and installation. Combined flat and spatial truss systems have many of these properties.
using modern calculation base, the achievements of
construction technology, techniques of artificial control
efforts and strains the combined systems of truss type are
effective load-bearing structures of the 21\textsuperscript{st} century.

2. Concept Headings

The article is aimed at publishing the proposals for improving
the design shapes of hybrid support systems for buildings
and facilities, methods of forming constructive solutions,
and techniques of their manufacture and assembly.

The proposed concept of improving hybrid structures
is based on the analysis of force interaction and the
 corresponding spatial orientation of rigid and flexible
elements of structural systems and appropriate and
effective redeployment of forces between the most and
least stressed elements.

The suggested materials allow designers and
researchers of constructions persistently to take advantage
of the hybrid bearing systems of buildings and facilities,
and improve the efficiency of their use.

3. Results and Discussion

3.1 Spatial Crosswise Strut Systems (SCSS)

The authors of this study consider metallic combined systems
including rigid and soft rod elements. Rigid rod elements
that in some cases can be manufactured from other materials
consist, as a rule, of stiffening beams that operate under the
conditions of bending tension and take the thrust forces from
the flexible elements and from the support pillars or the sag
rods, i.e. from the elements that connect the stiffening beams
with the flexible elements or the tie bars. Flexible elements
are manufactured either as tie bars of the broken-line shapes
that make up the strut frame system together with the pillars,
or as the straight line stay roosts that represent the stress-
yielding supports for the rigid rods. The combined systems
can feature pre-stressing.

In this respect the hybrid (combined) structures of
buildings and constructions are most promising and
economically practicable\footnote{A number of constructive solutions
have been suggested and developed for the so-called
Spatial Crosswise Strut Systems (SCSS) that are based on
applying the cross-shaped strut beams consisting of the
roof beams reinforced by the tie bars\footnote{For the purposes
of investigating the specific features of the crosswise strut
systems the calculation algorithms have been developed
that enable determining their stress-deformed conditions
at the stages of pre-stressing, installation and operation\footnote{The
stress-deformed conditions of SCSS with free hinge supports of the rigid shape are described precisely enough
for practical purposes by the differential equation as follows:
\begin{equation}
E_{Jx} \frac{d^4w}{dx^4} + E_{Jy} \frac{d^4w}{dy^4} = (q_x + H_x \frac{d^2z_x}{dx^2}) + (q_y + H_y \frac{d^2z_y}{dy^2}) \tag{1}
\end{equation}

Where: $E_{Jx}$ - bend stiffness values of the crossed
strut beams of the relevant directions; $H_x$; $H_y$ - strength
of self-tensioning in the tie bars of the relevant directions
under the roof loading; $q_x$; $q_y$ - modified load intensity per
unit of length of the strut girders of the relevant directions;
$z_x$; $z_y$ - distance between the axes of the roof-beams of
the strut girders and the axes of the relevant tie bars. The
numerical analysis of the deformed conditions of SCSS
blocks at the stress-yielding shape has been undertaken
that makes it possible to formulate the recommendations
on designing the stiffness ratios of the regular strut girders
and the shape diaphragms.}}

The numerical analysis has shown that in all cases
under consideration the most practicable way to design

One of the areas of improvement of the efficiency
of the construction process in erecting industrial and
civil buildings and constructions for different purposes
is represented by wider application of the flat and the
spatial hybrid (combined) systems of the strut frame
type. Constructive forms of the flat and of the strut frame
spatial hybrid (combined) systems stimulate applying
the advanced shapes, high-strength steel, light alloys
simultaneously making it possible and easy to regulate
stress and tension artificially, to apply simple joint
connections, to be practicable in terms of manufacturing
and installation. The authors have developed the
principally new constructive forms of flat and spatial
light hybrid (combined) systems of strut frame type
at the methods for their manufacturing,
installation and reinforcement that take into account
the relevant conditions of construction, reconstruction
and major overhauls of buildings and constructions.
The technical solutions have been protected by the
industrial patents\footnote{The technical solutions have been
protected by the industrial patents1-11.}.

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The numerical analysis has shown that in all cases
under consideration the most practicable way to design
SCSS blocks was to make them close to square in their plane configuration. Thereat, in the blocks with one stress-yielding diaphragm shape the ratio between the bent stiffening bars and the regular strut girders should be selected in the range of $\eta \geq 2...2.5$, and in the blocks with two parallel diaphragms it should be taken in the range of $\eta \geq 3...3.5$. The rational correlations between the bent stiffening bars and regular direct and crosswise strut girders are within the range of $1...1.418$. The large scale model of SCSS with plane dimensions of $6 \times 7.2$ m has been manufactured and tested. Full-scale SCSS of the roofing with plane square of circa 425 sqm has been experimentally investigated at the flexible stage of its operation for the first time. The results of the investigation showed that the structure under investigation could be regarded as a linearly deformed system. The strain-stress state component values obtained in the course of the tests are satisfactorily consistent with the relevant theoretical values. As a result of the investigations, the crosswise strut systems with spans of 15...30 m have been used at several objects of transportation facilities.

### 3.2 Stand-Alone Spatial Strut Frame Structures

A number of stand-alone spatial strut frame structures have been suggested and developed that represent the hybrid (combined) systems that consist of the roof bars reinforced by upper and lower tie bars placed in space relative to the roof bar and ensuring stable and reliable operations of the structure during installation and under operational loads shown in Figure 1 and 2. Such systems can be successfully applied as collar beams of the rigid cross-bars and other stand-alone constructions, and also as the component elements of the flat roofing structures of different buildings. The operations of such structures have been investigated: the specific features of their stability calculations have been determined, the rational parameters have been identified, and the methodology for the calculations at the flexible-plastic stage of the material has been developed. The pilot structures have been investigated in laboratory conditions and in-situ.

Based on the theory of the spatial stability of thin wall rods which was developed by and took into account the limitations acceptable for the structures under consideration, the general equation of spatial stability was obtained for the combined strut frame type system with the stiffening beam that possesses two axes of symmetry in its section. This equation makes it possible to investigate the stability of the strut frame constructions under different types of external loads and at the stage of their pre-stressing within the limits of the flexible operations of the material. Particularly, when the strut frame structure is affected only by the external longitudinal force $P$ applied at the ends the solution to this equation makes it possible to determine the critical values of the longitudinal load that correspond to Eulerian form of the stability loss in each of the planes and to the longitudinal torsion of the structure:

$$P_{cr} = \frac{EJ_0 n^2 \pi^2}{\lambda^2 L^2}; P_{cr2} = \frac{EJ_0 n^2 \pi^2}{\lambda^2 L^2}; P_{cr} = \frac{EJ_0 n^2 \pi^2}{L^2} + GJ_d.$$

Where: $\lambda^2$ – factor that characterizes the effects produced by the tie bars on the value of the Euler critical force in strut frame structure in the relevant plane and that changes in the range of $0.25 \leq \lambda^2 \leq 1$, depending on the ratio between the stiffness values of the beam and of the tie bars; $GJ_d$ – modified torsion stiffness of the beam taking into account its pre-stressing; $r$ – radius of the nucleus of the stiffening beam section. Among three critical values of the load the lowest value shall be regarded as design value.

The effects produced by the forces of the pre-tensioning of the tie bars on the value of the external critical force have also been investigated. The formulae have been obtained for determining the critical value of the external longitudinal load $P_{cr}$ with simultaneous effects produced by the pre-tensioning of the tie bars $H_0$ and with the decreased stability of the strut frame structure in one or two semi-oscillations accordingly:

$$P_{cr,1} = \frac{\pi^2 EJ_0}{L^2} \cdot \frac{H_0}{m^2} \quad \text{or} \quad P_{cr,2} = \frac{\pi^2 EJ_0}{L^2} \cdot \frac{H_0}{m^2},$$

where $m$ is the number of panels in the strut frame beam.

A serious but poorly investigated problem is represented by the behavior of the pre-stressed strut frame systems under the conditions of the combined effects produced by both static and dynamic loads, particularly those caused by snow, ice, wind, emergency conditions, industrial seismicity, generated, for example, by transport vehicles, by process equipment operations, etc. The oscillations of such systems are of nonlinear nature.
Mechanical and mathematical model has been developed that makes it possible to take into account the abovementioned factors; thereat, the initial problem has been represented as a system of three differential equations of the first order in terms of time and of the fourth order in terms of the coordinate with the relevant boundary conditions.

The equation of the space vibrations of the beam with spatial strut frame shall be represented as follows shown in Figure 1 and 2:

![Figure 1. Physical configuration of Spatial Strut Frame System.](image)

![Figure 2. Section A-A in Figure 1.](image)

where: \( m \) – specific (per unit of length) mass of the beam; \( y_0(x), z_0(x), y(x,t), z(x,t) \) – initial and current coordinates of the longitudinal axis of the stiffening beam; \( q(t) \) – current turning angle of the beam; \( j_0 \) – initial inclination angle of the tie bar; \( t \) – time; \( x \) – longitudinal coordinate; \( i \) – number of the tie bar; \( f_i = f_i(x) \) – shape of i-tie bar; \( N \) – amount of the tie bars;

\[
H_i(x,t) = \text{projection of the force from } i\text{-tie bar on axis } x;
\]

\( x \) – coefficient of internal resistance; \( q_j(x,t) \) – external load on the beam across the relevant axes; \( g_0 \) – angle of inclination of the line of the load force toward axis \( z \); \( l_0 \) – length of the “lever”; \( y_0 \) – angle between the line of the load force and the “lever”; \( e_j \) – type of force: 0 – of constant direction, 1 – tracing;

\[
\begin{align*}
\sum m_k \frac{\partial^2 y}{\partial t^2} + \sum H_k \left( \frac{\partial^2 \left( f_k \cos \left( \varphi_k \theta + \theta \right) \right)}{\partial x^2} - \Theta \left( \frac{\partial^2 \left( f_k \theta \right)}{\partial x^2} - \Theta \right) \right) - H \left( \frac{\partial^2 \left( \gamma \theta \right)}{\partial x^2} + \Theta \left( \frac{\partial^2 \left( \gamma y \right)}{\partial x^2} + \Theta \right) \right) + 2\xi \frac{\partial^2 \gamma}{\partial x \partial t} &= \sum q_i \sin \left( \varphi_i c + \theta \right) + F_i; \\
\sum m_k \frac{\partial^2 z}{\partial t^2} + \sum H_k \left( \frac{\partial^2 \left( f_k \cos \left( \varphi_k \theta + \theta \right) \right)}{\partial x^2} - \Theta \left( \frac{\partial^2 \left( f_k \theta \right)}{\partial x^2} - \Theta \right) \right) - H \left( \frac{\partial^2 \left( \gamma \theta \right)}{\partial x^2} + \Theta \left( \frac{\partial^2 \left( \gamma z \right)}{\partial x^2} + \Theta \right) \right) + 2\xi \frac{\partial^2 \gamma}{\partial x \partial t} &= \sum q_i \cos \left( \varphi_i c + \theta \right) + F_i; \\
\sum m_k \frac{\partial^2 \theta}{\partial t^2} - \sum H_k f_i \left( \frac{\partial^2 \left( f_k \theta \right)}{\partial x^2} - \Theta \right) - \left( G_{I_d} + r^2 \right) \frac{\partial^2 \theta}{\partial x^2} + \Theta \left( \frac{\partial^2 \theta}{\partial x^2} + \Theta \right) + 2\xi \frac{\partial^2 \gamma}{\partial x \partial t} &= \sum q_i l_i \cos \left( \varphi_i + \left( 1 - c \right) \theta \right) + M_i.
\end{align*}
\]

The first two equations reflect the bending vibrations and the third one reflects the torsion vibrations. Upon substituting the variables and the relevant boundary conditions the initial problem can be put down as a system of differential equations of the first order in terms of time and of the fourth order in terms of the coordinate.
To solve this system of equations the authors used the explicit Runge-Kutta-Merson method of the fourth order of precision in terms of time with automated control over the precision of the solution. For the purposes of space sampling the central difference scheme of the second order of precision has been applied. The calculation algorithm has been realized within the framework of ImpulsT software package. The developed mechanical and mathematical model makes it possible to determine the stress-deformed conditions of the combined systems that are simultaneously affected by static and dynamic loads taking into account the nonlinear factors and the history of loads.

The analysis of the operations of the structures under consideration showed that the behavior of the pre-stressed combined systems under dynamic loads differs considerably from that under similar rod loads. Thus, the frequency of proper vibrations of the rigid rod systems \( w_0 \) does not depend on the value of the initial agitation; and for the combined systems this assumption holds only under the conditions when the tie bars are not disconnected. When the value of the initial agitation increases and the tie bars are disconnected the frequency of the proper vibrations decreases. With resonating external agitation in the combined system the alternate disconnection of the tie bars stabilizes the amplitude of the vibrations at some certain value and switches the vibrations into the oscillation beats mode which can be regarded as proper absorber of the vibrations. The discovered properties of the combined strut frame systems should be taken into account in the course of developing their real design. The experimental investigations of the vibrations of the preliminary stressed strut frame systems have proved the correctness of the adopted theoretical assumptions.

### 3.3 Strut Frame Beams with Active Shapes of the Tie Bars

The investigations in the sphere of creating the forms of the combined systems resulted in developing the strut frame structures with active shapes of the tie bars shown in Figure 3 that can improve the durability of the system by 5...12% without any additional material consumption. Based on the modified Nelder-Mead simplex method, a mathematical model has been developed for optimizing the shape of the tie bars and the cross sections of stiffening beams in the strut frame structures under different parameters of the system.
and stability under the effects of the external factors. This approach makes it possible to find maximum value of the strength of the system under the preset external loads and at the pre-set level of the pre-tensioning of the tie bars $H_0$ for strut frame structures of different topology. The obtained model has been realized in the MATLAB software package.

It has been established that the classical shape of the tie bars similar to the shape of the external loads torsion moment diagram in the basic system is an optimum one only at the level of their pre-stressing that ensures the moment less operations of the stiffening beam. Active shapes of the tie bars have been discovered that make it possible to redistribute the bending moments on the whole length of the stiffening beams and that ensure relative increase in the strength of the system by 5…23 %.

### 3.4 Strut Frame Systems with Combined Pre-Stressing

The analysis of the evolutional development of the preliminary stressed steel structures justifies the assumption that one of the most promising areas of improvement in developing the methods for pre-stressing of the engineering structures is represented by the combined pre-stressing that includes different techniques of artificial control of stress and deformation. A number of methods of combined pre-stressing have been suggested and implemented in practice\textsuperscript{11,20}. In particular: straining the strut cross-beam of the frame with the tie bar with simultaneous bending of the pillars; simultaneous bending of the parts of the composite stiffening beam of the cross-bar with bending of the pillars of the frame; straining with the tie bar and with the bending of the cross-bar of the frame system; bending the parts of the composite stiffening beam in one direction with simultaneous stressing by the tie-bar; mutual bending of the parts of the composite stiffening beam and straining the tie bar.

In laboratory environment a number of strut frame beams featuring span of 3.6 m with perforated walls have been investigated applying the combined method of the pre-stressing. The results of the investigations proved that preliminary bending of the beam combined with tensioning the tie bars of the strut frame structure make it possible to obtain more favorable pattern of distributing stresses across the section of the perforated stiffening beam and to increase the area of its flexible operations.

The combination of the pre-stressing by mutual bending of the parts of the composite stiffening beam with simultaneous stressing of the tie bar in the strut frame system has been studied in more detail. The strength criterion of the practicability of the preliminary bending of separate tee bars that form the section of the beam towards each other within the limits of their elasticity have been determined:

$$\Omega = \frac{W_{01}(1-\mu_m \rho_0)}{W_1(q\mu_0 \rho_0 - 1)} > 1.$$  

Where $W_{01}, W_1$ – moments of resistance of a particular tee bar and of the whole section relative to the upper leg in the calculated opening in the I-bar; $m_m, m_q, J, r_0$ – values that depend on geometrical and strength properties of the system and on the scheme of loading. $\Omega$ – the value that reflects the practicability of preliminary bending; $\Omega < 1$ – strength of the stiffening beam is determined by the stress in the wall of the tee bar and thus the preliminary bending is deemed impracticable; $\Omega = 1$ – the stress limit is achieved in the leg and in the wall of the tee bar simultaneously, and the bending is deemed impracticable; $\Omega > 1$ – the strength of the beam is determined by the stress in the compressed leg of the tee bar. In this case the preliminary bending improves the strength of the stiffening beam. In cases when the stiffening beam operates without moments the preliminary bending always improves the strength of the stiffening beam irrespective of the geometric characteristics of the latter.

The equations have been found for determining the strength of the perforated stiffening beams in the strut frame systems featuring combined pre-stressing at the flexible stage of the material operations. The strength criterion has been determined that makes it possible to evaluate the practicability of the preliminary bending of the stiffening beams. The effects produced by the combined pre-stressing on resistibility have been analyzed depending on the parameters of the strut frame structures. It has been established that there is a relative value of the releasing effect of the tie bars at which the maximum effect from the combination of the pre-stressing can be achieved. This value has been found together with the rational, in terms of strength, correlations between the component elements of pre-stressing. It has been established that the preliminary bending increases the torsion strength of the open shape perforated beams. The relevant equations have been determined that take into account the preliminary bending for the perforated beam.
I-beams. Increase in the torsion strength that results from bending can reach 25…60% depending on geometrical characteristics of the section and on the intensity of the stress. Under the conditions of the restricted torsion the preliminary bending reduces the level of bi-moment normal stress by 30…40% depending on the parameters of the system and on the conditions of loading. A number of tests have been undertaken with the strut frame beams featuring the perforated walls and the spans of 3.6 m under the conditions of crosswise bending and restricted torsion.

It has been experimentally proved that preliminary bending makes it possible to redistribute the stress favorably across the section of the stiffening beam and to increase the area of the flexible operations of the system. In cases with the pilot structures the increase in strength amounted to 13.3%. The calculated and experimental data are satisfactorily consistent. The plastic deformations at the ends of the walls of the tee bars of the weakened sections of the perforated stiffening bars do not affect the deformation properties of the system and do not represent the boundary conditions of the structures. During the tests carried out with the strut frame beams under conditions of bending and torsion the preliminary bending used to decrease the level of bi-moment normal stress by 25-30%. The pre-stressing of the tie bars used to increase bi-moment stress by 7-13%. Total positive effect from the combined preliminary stressing amounted to 17-23%. The developed method of the pre-stressing has been implemented at several objects that have been erected in Saint-Petersburg.

4. Conclusion

Apart from their obvious advantages, the combined systems have some disadvantages as well; namely: sensitivity toward the uneven schemes of loading results in additional consumption of metal for stiffening beams; the necessity to arrange special anchoring supports for fixing the pre-stressed tie bars and for their straining increases the laboriousness of their manufacturing; limited forces of the pre-tensioning of the tie bars in terms of the stiffening beam stability reduce the effect that results from the artificial force control. In all, the investigations and practical developments make it possible to overcome many of the abovementioned disadvantages and to use the additional internal reserves of the strut frame systems. Based on the modern calculation capabilities, on the achievements of the construction techniques and on the advanced instrumentation for the artificial force and deformation control, the combined strut frame systems represent the efficient load-bearing structures of the 21st century.

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