Legal aspects of the use of collective means of protection in the construction of industrial buildings

Victor Brodskiy[1] *Saidahmed* Mutsalov [2]

[1]Moscow State University of Civil Engineering, Moscow, Russia

[2]Kadyrov Chechen State University, Grozny, Russia

Abstract. The article presents conditions for ensuring the safe performance of construction and installation works during construction/reconstruction of industrial buildings and facilities of various purposes, based on the use of fall arrest nets, which are collective protective equipment for preventing work-related injuries in case of a person's or an object's potential fall from height. The article specifies the basic elements of these devices where synthetic netting materials are suggested as the most pacing factor of the required protection degree. Consideration is given to governing parameters of fall arrest safety nets that make it possible to ensure the safety of works at heights. This produced net deflection values that are acceptable for conditions under which construction is carried out, with required contour-rope tension values. The value of the maximum negative acceleration that acts on a body falling from height to the net was assessed. Herewith, the performed calculations showed, based on relatively large dimensions of the fall arrest device's net fabric, that overloads that occur when catching fallen objects are insignificant and do not require that additional equipment be used to reduce dynamic loads.

Keywords: construction, industrial buildings, work at height, catching nets

1 Introduction

Measures for ensuring the safety of works at heights for a particular facility are established in organizational and technical documentation [1,2], which recently has been increasingly recommending the use of collective protective equipment based on netting materials made of synthetic fibers when erecting residential and public multistory buildings. To determine optimal parameters and protective properties of this equipment, we carried out studies that enabled us to establish structural layouts of devices and dimensions of load-bearing brackets and nets to make sure that falling objects are caught and allowed us to identify shock absorbers' characteristics decreasing dynamic effects to safe values in case of a person's fall [3,4,5].

The performed tests and operation of fall arrest devices designed and manufactured according to the conducted studies confirmed the results of theoretical calculations, while the determination of optimal conditions for manufacturing and distributing devices at facilities being erected gives evidence that their wide application in construction operations offers promise [6]. The obtained results allowed us to develop provisions that were included in regulatory documentation.

With that in mind, it seems reasonable to further expand the applications of fall arrest devices using netting materials. At the same time, fall arrest devices with netting materials have

[1] Corresponding author: viktor.37@mail.ru

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failed so far to find appropriate use in national practice, particularly in the construction and reconstruction of industrial-purpose facilities.

A problem was therefore set to theoretically and experimentally study the operation of fall arrest devices with netting materials that are intended for single-story industrial buildings under construction. This protective equipment shall ensure safe working conditions during the installation of structures, utility lines, and lighting and ventilation systems as well as during repairs performed at heights and reconstruction of manufacturing facilities [7].

A structural layout of a fall arrest device for single-story industrial buildings as follows is proposed (Fig. 1). Net fabric that can cover a building bay up to 24 m long shall be fixed along the perimeter to ropes 8 mm in diameter. The ropes shall be passed through special clamps fastened on the building's columns. The ropes shall be sequentially tensioned using a special mechanism, which can be a manually operated winch, thereby lifting the protective net to the required height.

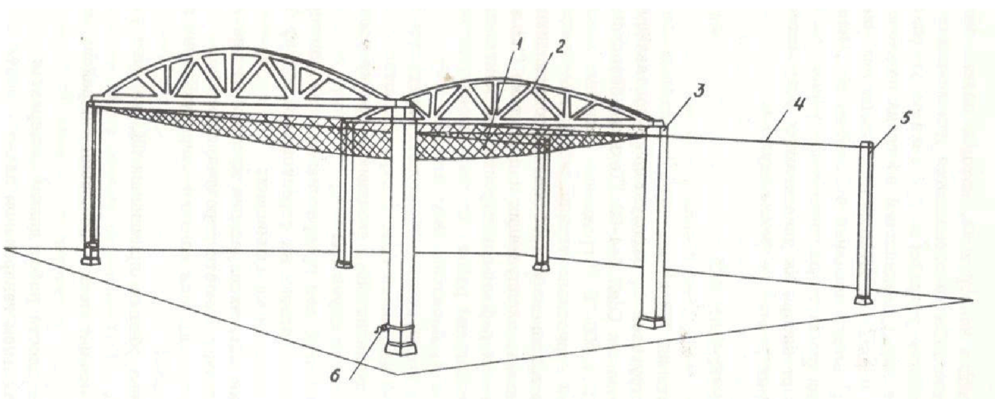

Fig. 1—A structural layout of a fall arrest device with netting materials for industrial buildings
1—net fabric, 2—truss, 3—supporting clamp, 4—contour rope, 5—building's column, 6—tensioner

The specific nature of such devices is determined first of all by a significant distance in the horizontal plane between potential points for attachment of the fall arrest net's elements to structures of the building. This will call for solving the principles of the devices' attachment to the building's load-bearing structures and fixing the net fabric to supporting elements, which in this case are tensioning ropes.

2 Materials and Methods

Tests of prototypes established that the net fabric's pitch of deflection when tensioning a rope with a force of 6860 N reaches 4 m; the rope elongation at this load is 2.5 m, and the rope's pitch of deflection is approximately 1 m. Hence, a need for sequential solutions to the following problems:

1) determine a dependence of the pitch of an unloaded net's deflection on the securing-rope tension value;

2) assess dynamic effects on a fallen object when it is caught by a fall arrest device.

To determine the dependence of the pitch of the unloaded net's deflection on the securing-rope tension value, the pitch of the unloaded net's deflection shall be determined first. As the conducted analysis of available literature showed, the calculation of nets is very complex, even in the static case, and requires that equilibrium equations for each node of the net are generated and that the obtained equations, which are nonlinear as a matter of fact, are solved using a computer. In addition, the problem becomes more complicated in cases when the net has points of support only at some nodes of the contour. The calculation is usually performed according to a strain-method scheme: determine a deflection with supported nodes of the contour and then a deflection resulting from a shift of the contour nodes.

Therefore, a simplified analytical method for solving this problem is offered.

First, we determine the deflection of a contour thread under the action of the net weight and tension applied to the contour, and then we determine the deflection of a thread located perpendicular to the line of a contour whose deflection is already known, considering a possibility of inward shifting of the contour (Fig. 2).

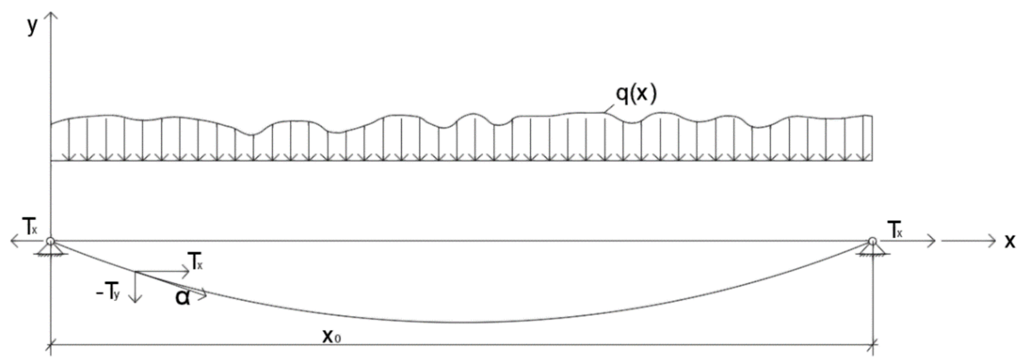

Fig. 2—A diagram of a contour thread's deflection under the action of the net weight and tension applied to the contour rope

At the same time, when objects fall onto a fall arrest device, account must be taken of a factor like the potential occurrence of dynamic overloads that might cause a failure of fall arrest devices' structures, injuries of fallen workers, and other undesirable effects.

An impact action occurs when something falls on a fall arrest device. The force of the impact on the falling object when coming in contact with the surface of the fall arrest net depends on the mass and movement speed of this object. If the object before the fall was at rest, its movement intensity is interrelated with height and gravitational acceleration. The object's falling speed in practical terms is characterized by its pre-fall position height [8].

To solve the first problem of determining the dependence of the pitch of the unloaded net's deflection on the securing-rope tension value, let us introduce notations as follows [9]:

$f(x)$ is a deflection of the thread;

$T_x(x)$, $T_y(x)$ are components of the thread tension at point X;

q(x) is an external load on the thread.

An equation of equilibriums of an elementary segment of the thread is as follows:

$$\vec{T}(x) + \vec{T}(x + \Delta x) + q(x)\,\Delta x = 0$$

or projections on the Cartesian axes:

$$-T_x(x) + T_x(x + й\Delta x) = 0 \qquad (1)$$

$$-T_y(x) + T_y(x + \Delta x) - q(x) = 0 \qquad (2)$$

It follows from equation (1) that $T_x(x) = T_x = const$

By dividing the second equation by Δx and passing to the limit, we obtain

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$$\frac{\partial T_{y(x)}}{\partial x} = q(x)\ , \quad (3)$$

whence $$T_y(x) = \int_0^x q(x)dx + c_1, \quad (4)$$

but $f(\mathrm{x}) = \tan tan\ \alpha = \frac{T_y(x)}{T_x}$, whence

$$f^{`}(x) = \frac{1}{T_x}\{\int_0^x q(x)dx + c_1\} \quad \text{and}$$

$$f(x) = \frac{1}{T_x}\{\int_0^x(\int_0^u q(\mathfrak{z})d\mathfrak{z})du + c_1x + c_2\} \quad (5)$$

Boundary conditions will be equalities of thread deflections to zero at the bay ends, i.e., $f(0) = 0;\qquad f(x_0) = 0.$

From the first condition, it follows that $c_2 = 0$, and from the second one, that

$$\mathrm{c}_1 = -\frac{\int_0^x(\int_0^u q(\mathfrak{z})d\mathfrak{z})du}{x_0} \quad (6)$$

Thus, expressions (5) and (6) give us the sought-for thread shape at random load q(x). In our case for a net that is unloaded, we can take q(x) = const.

By plugging q(x) = q into formulas (6) and (5), we obtain the relation as follows:

$$f(x) = \frac{1}{T_x}\{\int_0^x(q\int_0^u d\mathfrak{z})du - \frac{qx_0}{2}x\} = \frac{q}{2T_x}(x^2 - x_0x) \quad (7)$$

T_x approximately corresponds to the tension force applied to the contour rope.

To determine the deflection of an "inner thread," we adopt a computational model shown in Fig. 3.

In this model, BC is a direct brace, while AB and CD are weightless rigid rods that can freely rotate around supports A and D, respectively. Their length f is numerically equal to the value of the contour-thread deflection at this point [10]. Considering the load for a freely hanging net to be uniformly distributed along the bay, we take the thread shape as a quadratic parabola, which is written as $y = Ax^2$, and since rods AB and CD are weightless their direction coincides with that of the tangent and that of the thread at points B and C; then,

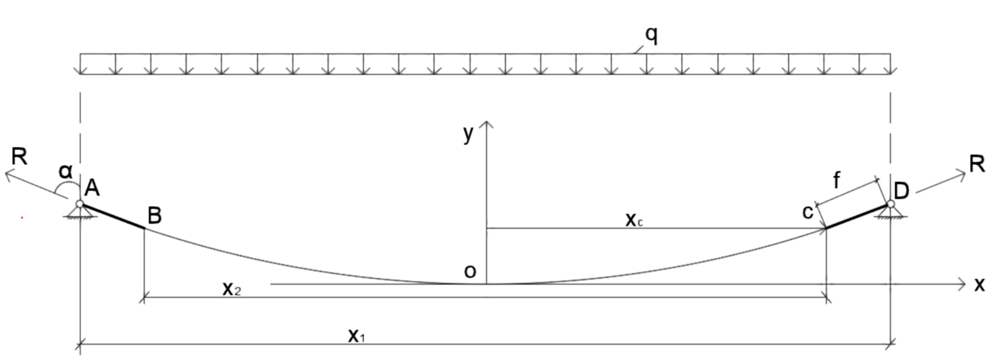

Fig. 3—Deflection determination model for the net fabric's "inner thread"

$$y'\left(x_c\right) = 2Ax_c = \cot cot\,\alpha \qquad A = \frac{\cot cot\,\alpha}{2x_c} = \frac{\cot cot\,\alpha}{x_2}.$$

Let us write an expression for the parabola length: L

$$L = 2Ax_c\sqrt{x_c^2 + \frac{1}{4A^2}} + \frac{1}{2A}.$$

Substituting $A = \frac{\cot cot\,\alpha}{x_2}$ and considering that $\sqrt{\frac{x_2^2}{4} + \frac{x_2^2}{cot^2\alpha}} = \frac{x_2}{2\cos cos\,\alpha}$, we obtain

$$L = x_2\left\{\frac{\cot cot\,\alpha}{2\cos cos\,\alpha} + \frac{\ln ln\left[\cot cot\,\alpha\left(1+\frac{1}{\cos cos\,\alpha}\right)\right]}{2\cot cot\,\alpha}\right\}.$$

(8)

Solving this equation together with the equation

$$\alpha + x_2 = x_1 \qquad (9)$$

by the method of successive approximations, we determine α and x_2 and then solve the problem of determining thread deflections in the same way as for the contour case and taking $x_0 = x_2$ and $T_x = R\sin sin\,\alpha$, where $\alpha = \int_0^{x_c} q(x)\,dx$. After that, it becomes possible to find net deflection values.

When considering the second problem for assessment of dynamic effects on a fallen object when it is caught by a fall arrest device, we determine the value of maximum negative acceleration acting on a body with mass *m* that falls on the net from height *H*. In this case, a model can be used that is similar to an oscillatory system shown in Fig. 4.

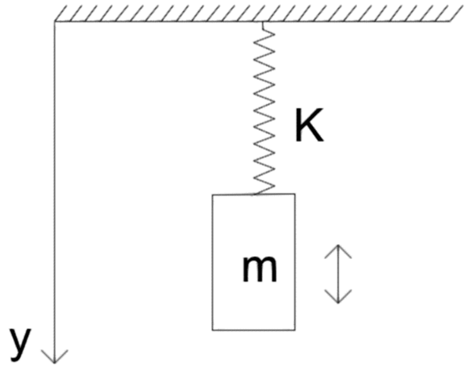

Fig. 4—A model of negative acceleration acting on an object falling from height

For this system in the free-oscillation regime, a motion equation is written as [11]

$$m = \frac{d^2y}{dt^2} + ky = 0.$$

Initial conditions are taken as follows:

$$\frac{dy}{dt}\Big|_{t=0} = V_0 \quad \text{(a)} \qquad y\big|_{t=0} = 0 \quad \text{(b)}.$$

By denoting $\omega^2 \equiv \frac{k}{m}$, we can obtain the solution of the equation in the form as follows:

$$y = A\sin sin\,\omega t + B\cos cos\,\omega t.$$

From (b), it follows that B = 0, and from (a), that $A = \frac{v_0}{\omega}$.

Thus, $y = \frac{v_0}{\omega} \sin sin\, \omega t;$ $y_t'' = - v_0 \omega \sin sin\, \omega t;$

$$c' = \left| y''_{t_{min}} \right| = v_0 \omega, \text{ but } v_0 = \sqrt{2gH} \Rightarrow a = \sqrt{2gH \frac{k}{m}} \quad (10)$$

Now, we need obtain assessment of value k corresponding to elastic behavior of a real-life net fabric. To do so, we apply load P at some point of the net and determine the value of deflection f from this load at its application point. Then, we can calculate $k = \frac{P}{f}$, namely, as a ratio of the load to the deflection value.

3 Results

Let us perform a calculation for a net with plan dimensions 24 × 24 m and determine the pitch of its deflection for a case of applying contour-rope tensioning force T_x = 6860 N.

The total area of the net is equal to $S = L_c \times K_c = 24 \times 24 = 576$ m²,
where L_c is the width of a bay of the production building under construction, m;
K_c is the length of the net fabric located along the production building under construction, m.

Based on the weight of one square meter of the net u = 4.9 N/m², the total net weight will be

$$Q = 4.9 \times 576 = 2822.4 \text{ N}.$$

The load corresponding to the net's contour thread P is

$$P = \frac{Q}{2 \times L_c} = \frac{2822.4}{2 \times 24} = 58.8\, N/m.$$

The contour thread's deflection in the middle of the bay will be equal to

$$f(12) = \frac{58.8}{2 \times 6860} (12 \times 12 - 24 \times 12) = - 0.576\, m.$$

As preliminary studies in fall arrest devices determined a net mesh size of 50×50 mm, "inner" threads are spaced accordingly every l = 50 mm.

Then, the loading area of each thread will be

$$s = l \times L_c = 0.05 \times 24 = 1.2 \text{ m}^2.$$

Uniformly distributed load F acting on the thread is equal to

$$F = \frac{s \times u}{L_c} = \frac{1{,}2 \times 4.9}{24} = 0.245 \text{ N/m}.$$

Solving the system of equations (8) and (9), we obtain $\alpha = 61.5^0$.

Since $R_x = R \sin sin\, \alpha = 5.4\, N$, , considering this value of R_x, we can obtain the net deflection value

$$f_1 = \frac{0.245}{2 \times 5.4} (12 \times 12 - 24 \times 12) = - 3.26\, m.$$

This result is well consistent with experimental data obtained from tests. In addition, calculations performed with other values of T_x showed the results as follows:

at $T_{x_2} = 1500\, kg$, $f_2 = 2.28\, m$,

at $T_{x_3} = 2000\, kg$, $f_3 = 1.70\, m$.

Thus, a conclusion can be drawn that, in order to obtain net deflection values that are acceptable for the conditions of construction works, the contour rope's tension shall be increased from the initially proposed one approximately three-fold.

To solve the second problem, let us choose an object fall point corresponding to the center of the net as an example. If the weight of the falling object is $P = 980\, N$, then, according to the above method, we obtain that

$$f = 1.6 \text{ m and } k = \frac{980}{1.6} \text{ N/s}^2.$$

If the fall height is H = 6 m, the overload from (10) will be

$$a = \sqrt{2 \times 10 \times 6 \times \frac{61}{100}} \cong 9 \frac{m}{s^2}.$$

As can be seen from the obtained result, when an object falls on a fall arrest net, the occurring dynamic overloads of approximately 9g allow safe conditions of construction and installation works at height to be created during the construction of industrial buildings.

4 Findings

As a result of the performed work, the following conclusions can be drawn concerning fall arrest devices with netting materials for industrial buildings under construction and reconstruction:

1. Installation of fall arrest nets on large-bay industrial buildings under construction for limiting the net fabric's sag within 2 m requires that a contour-rope tension force of up to 19.6 kN is created.
2. It is feasible to use intermediate ropes (stiffeners) to decrease the net fabric's deflection in fall arrest devices.
3. Because of the relatively significant dimensions of net fabrics, dynamic overloads acting if objects fall on a fall arrest device have acceptable values and require no additional use of special shock-absorbing devices.
4. The use of netting materials in collective protective equipment facilitates the ensuring of safe performance of construction and installation works at heights during construction and reconstruction of industrial buildings.

References

1. Oleynik, P. P., *Industrial Mobile Methods of Construction of Enterprises, Buildings, and Structures:Monograph* (Moscow:ASV Publishing House, 2021), 488, ISBN 978-5-4323-0377-6
2. Shirshikov, B. F., Zhadanovskiy, B. V., et al., *Organizational and Technological Solutions for Occupational Safety in Work Execution Designs* (Moscow: ASV Publishing House, 2015), 100. ISBN: 9785432301154
3. Brodskiy, V., "Parameters of the Safety and Fall Arrest Nets in Buildings under Construction," *XXII International Scientific Conference "Construction—the Formation of Living Environment" (FORM-2019)*, Tashkent City, Uzbekistan (2019)
4. Brodskiy, V., "Dependence of Trapping Nets' Protective Properties on Structural Layout," *VIII International Scientific Siberian Transport Forum Trans-Siberia 2019, "Achievements in the Field of Intelligent Systems and Computing" Book Series* (AISC, Volume 1116), Volume 2 (2019), pp. 277-284, https://doi.org/10.1007/978-3-030-37919-3_27 (doi: 10.1007 / 978-3-030-37919-3_27)
5. Brodskiy, V., "Organization of Safe Execution of Works with the Use of Trapping Nets," *VIII International Scientific Conference Transport of Siberia—2020 IOP Conf. Series: Materials Science and Engineering 918* (2020), 012016, IOP Publishing, doi:10.1088/1757-899X/918/1/012016
6. Brodskiy, V., "Simulation of Fitting of Construction Organizations and Erected Buildings with Collective Protective Equipment," *XXI International Scientific Conference "Construction—the Formation of Living Environment,"* April 25 to 28 2018, Moscow, NRU MGSU (FORM-2018) (2018), 365, UNSP 062008
7. Zhadanovskiy, B. V., Sinenko, S. A., Kuzhin, M. F., "Rational Organizational and Technological Charts of Construction and Installation Works under the Conditions of

Reconstruction of an Operating Enterprise," *J. Technology and Construction Operations Organization*, No. 9 (2014), pp. 51-55
8. Butenin, N. V., Lunts, Ya. L, Merkin, D. R., *Theoretical Mechanics Course* (Moscow: Lan, 2023), 736. ISBN978-5-8114-5552-2
9. Yevtushenko, Yu. G., *Methods for Solving Extremum Problems and Applications Thereof in Optimization Systems* (Moscow: Nauka, 1982), 432
10. Volkov, V. T., Yagola, A. G., *Integral Equations. Calculus of Variations. Problem-Solving Methods* (M. V. Lomonosov Moscow State University, Faculty of Physics, Moscow: Universitet Book House, 2013), 137, ISBN 978-5-98227-315-4
11. Arnold, V. I., *Ordinary Differential Equations* (Moscow, MTsNMO Publishing House, 2012) 344, ISBN 978-5-94057-907-6