



## ANALYSIS OF THE STRESS STATE OF A LOAD CHAIN LINK UNDER STATIC LOADING CONDITIONS

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*Universalization of regulated indicators of safety factors for a wide range of technical industrial chains and scientific substantiation of the service life of such chains is an important national and economic task. The purpose of this work is to study the stress state of the links of round-link cargo chains and substantiate proposals for the selection of their safety factors for use in machines and mechanisms of general mechanical engineering. Based on a comprehensive analysis of the components of the stress state of the arc section of the cargo round-link chain, performed using the developed visual cognitive model of this section, and taking into account the results of experimental tests of the mechanical characteristics of round-link chains of calibers 3, 4, 5, 6, 8 of class G80 according to the ASTM A391 standard, made of 20MnNiCrMo5-2 steel, a “sensitivity threshold” of the destructive stress of the link was established as an alternative to the value of the ultimate strength of the material from which the chain links are made. At the same time, the level of confidence probability for the obtained results is not worse than 0.96. It is proposed that in the case of using the “sensitivity threshold” of the destructive stress instead of the value of the material strength limit for the manufacture of cargo round-link chains, it is advisable to use general engineering standards for safety factors, which vary within 1.5...2.5. Prospects for further research are determined, which should be aimed at universalizing the characteristics of mechanical strength of a wide range of technical industrial chains.*

*The proposed analytical approach enables the improvement of strength assessment methods and optimization of safety factors for cargo round-link chains used in general mechanical engineering.*

**Keywords:** round-link cargo chain, stressed state, safety factor, visual cognitive model, mechanical tests, ultimate strength, “sensitivity threshold” of destructive stress.

**Eq. 3. Fig. 7. Table. 3. Ref. 16.**

### 1. Problem formulation

The main areas of application of cargo round link chains are rafter and rigging elements for fastening, fixing and moving cargo in construction, industry and transport [1, 2, 3]; use as traction elements in winches, cranes, telfers and hoists [3]; in mining, metallurgy and agriculture [2, 4, 5]; in conveyors and elevators for handling bulk materials; as fencing, decorative elements and in everyday life [3].

The main feature of the use of cargo round link chains is the exclusively linear application of tensile forces in the direction of the chain axis. Even in cases of using chains as closed or open curvilinear contours, these contours are outlined by a chain line or the so-called catenary, a characteristic feature of which is that in the field of gravitational forces between individual chain links, only tensile forces act, directed at each point along the tangent to the chain contour [4, 6, 7, 8].

### 2. Analysis of recent research and publications





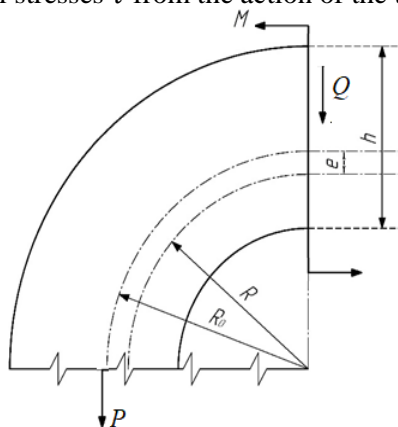
Analysis of the current state of the issue and formulation of a working hypothesis. Usually, the determination of the main physical and mechanical characteristics of cargo round-link chains is reduced to a mandatory procedure for checking their reliability (in accordance with the EN 818-2 standard). This procedure provides, in particular, a special test (EN 818-4 standard), which is carried out using special stands (Fig. 1) and consists in testing a sample of the chain (rigging sling) with an overload of 25% (static test) and 10% (dynamic test) compared to its standard load capacity [9, 10, 11].



**Fig. 1. Stand for testing round-link load chains**

“Technical Regulations for the Safety of Machines and Equipment” [1, 3] and requires a thorough study of the stress-strain state of chain links. It is such studies that should provide the development of proposals for choosing the optimal safety factor of the chain, taking into account the specific operating conditions of mechanical engineering products.

*Basic equipment and experimental research methodology.* As a graphic model of a link of a round-link cargo chain, the calculation scheme of a curved beam [15, 16], which is loaded with a longitudinal force  $P$ , and the corresponding bending moment  $M$  (Fig. 2). The analysis of the stress-strain state of a chain link involves a graphical synthesis based on the principle of superposition of normal stresses  $\sigma$ , which arise in the normal cross-sections of the link from the action of force  $P$ , moment  $M$  and contact with an adjacent link of the chain, as well as tangential stresses  $\tau$  from the action of the transverse force  $Q$ .

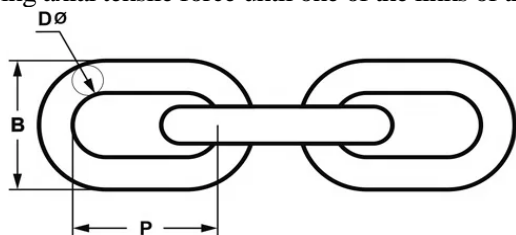


**Fig. 2. Graphical model of a chain link element:**

$P$  – longitudinal force  $M$  – bending moment,  $Q$  – transverse force;  $R_0$  – radius of the axis of the centers of gravity of the beam sections,  $R$  – radius of the neutral axis of the beam,  $e$  – displacement of the neutral layer of the beam relative to the centers of gravity of its sections,  $h$  – calculated size of the beam



For mechanical tests, specially prepared 5-link samples of cargo chains with short and long links of class G80 (Fig. 3) according to the ASTM A391 standard of caliber 3, 4, 5, 6, and 8 mm, made of 20MnNiCrMo5-2 steel, the chemical composition of which is given in Table 1, were used. Mechanical tests were carried out using a R-50M1 tensile testing machine (Fig. 4) and involved the implementation of static loading of chain samples with a gradually increasing axial tensile force until one of the links of the chain sample broke.



*Fig. 3. Sample circuits for testing:*

*D – caliber; P – pitch, which determines the length of the link; B – transverse dimension of the link*

*Table 1.*

*Chemical composition of 20MnNiCrMo5-2 steel*

| Chemical element | Carbon,<br><i>C</i> | Manganese<br><i>Mn</i> | Chrome<br><i>Cr</i> | Nickel<br><i>Ni</i> | Molybdenum<br><i>Mo</i> | Silicon<br><i>Si</i> |
|------------------|---------------------|------------------------|---------------------|---------------------|-------------------------|----------------------|
| Contents, %      | 0,20 – 0,25         | 0,80 – 1,20            | 0,30 – 0,40         | 0,30 – 0,40         | 0,10 – 0,15             | 0,15 – 0,35          |



*Fig. 4. R-50M1 tensile testing machine*

Based on the results of mechanical tests, the ultimate breaking force of a link of chains of caliber 3, 4, 5, 6, 8 and their ultimate strength (temporary resistance to fracture) under normal stresses were determined.

The basis for developing proposals for selecting optimal safety factors for chains for use in machines and mechanisms of general-purpose technological equipment was determined by the “Technical Regulations for the Safety of Machines and Equipment” in accordance with the Law of Ukraine dated January 15, 2015 No. 124-VIII On Technical Regulations and Conformity Assessment.

### 3. The purpose of the article

To investigate the stress state of the links of round-link load chains and substantiate proposals for the selection of their safety factors for use in machines and mechanisms of general mechanical engineering.

To achieve the declared goal of the work, the following tasks need to be solved:

- develop a graphical-analytical model of a link of a cargo round-link chain and perform a model analysis of its stress-strain state;
- based on the results of mechanical tests, determine the analytical dependence of the tensile strength (temporary resistance to fracture) of the chain on the main geometric features of its standard size;

- to substantiate proposals for choosing optimal safety factors for chains for use in machines and mechanisms of general-purpose technological equipment.

The object of the work is the stress state of the links of round-link cargo chains under the conditions of their operational loading by external forces.

Subject of the work. Components of the complete stress tensor taking into account internal forces and moments acting in the links of short-link and long-link cargo round-link chains.

#### 4. Results and discussion

To analyze the components of the stress state in the arc section of the chain link, a graphic cognitive model of this section (Fig. 5) is proposed, in an arbitrary section  $A-A$  and in which, when a longitudinal force  $P$  is applied, the chain stretches:

- stable bending moment  $M = 0,5P \cdot k = N \cdot k$  ( $0,5P = N$  – longitudinal force in the link shoulder;  $k$  – chain gauge);
- variable longitudinal  $N$  and transverse  $V$  forces, the magnitude of which is determined by the orientation (at an angle  $\alpha$ ) the cross-section under consideration  $A - A$ );
- power  $Q$  in the contact zone of two links with crossed axes, the intensity of which along the contact plane is  $q$ .

At the same time, the considered section of the link arc is distinguished by “technological transverse anisotropy”, which is formed as a result of technological deformation of the link rod (wire) around the crossbar. In an arbitrary cross-section  $A-A$  arc of a chain link, the contour of this deformed section is determined by a Maxwell oval, which causes the movement of the fibers of the neutral layer of the arc of the link towards the compressed fibers (Fig. 5 - section  $A-A$ ). Thus, the neutral axis of the arc of the link is determined by a certain radius, which is determined by the locus of the points of the centers of gravity of the set of arbitrary sections  $A-A$  (Fig. 5).

Based on the results of the analysis of internal force factors acting in an arbitrary cross-section of the arc of a round-link cargo chain link, the nature of the distribution of normal stresses was determined.  $\sigma_{\Sigma}$ , which are the sum of the stresses  $\sigma_M$  from the action of bending moment  $M$  and tensions  $\sigma_N$  from the action of longitudinal force  $N$ , as well as tangential stresses  $\tau_V$  from the action of transverse force  $V$  and contact stresses  $\tau_Q$  from the action of the contact force  $Q$ . Normal stresses  $\sigma_N$  lead to the development of microcracks of detachment (the edges of the crack diverge relative to each other) of the outer fibers of the arc of the link, and tangential contact stresses  $\tau_Q$  reinforced by the action of tangential stresses  $\tau_V$ , which are caused by a transverse force  $V$  cause the development of longitudinal shear cracks, a feature of which is the sliding of the crack edges one by one in the longitudinal direction.

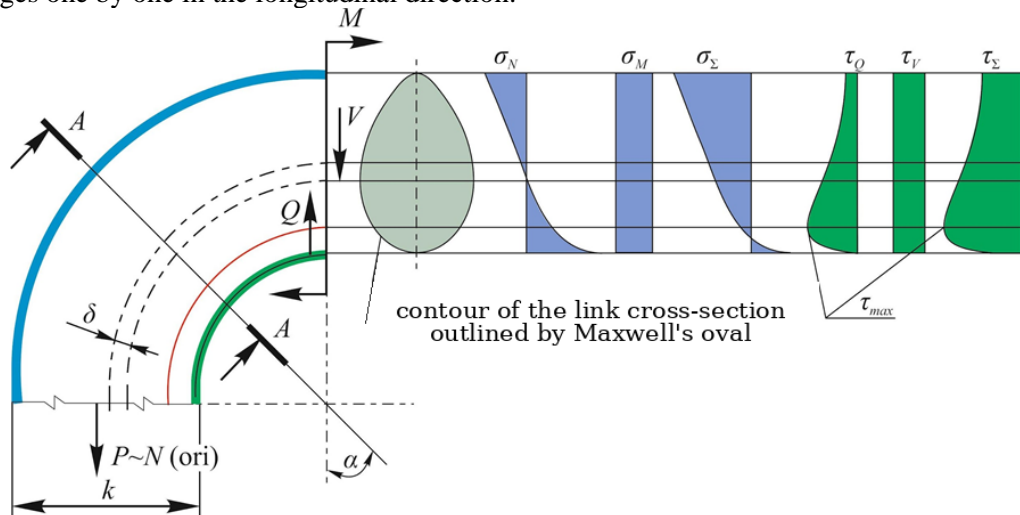
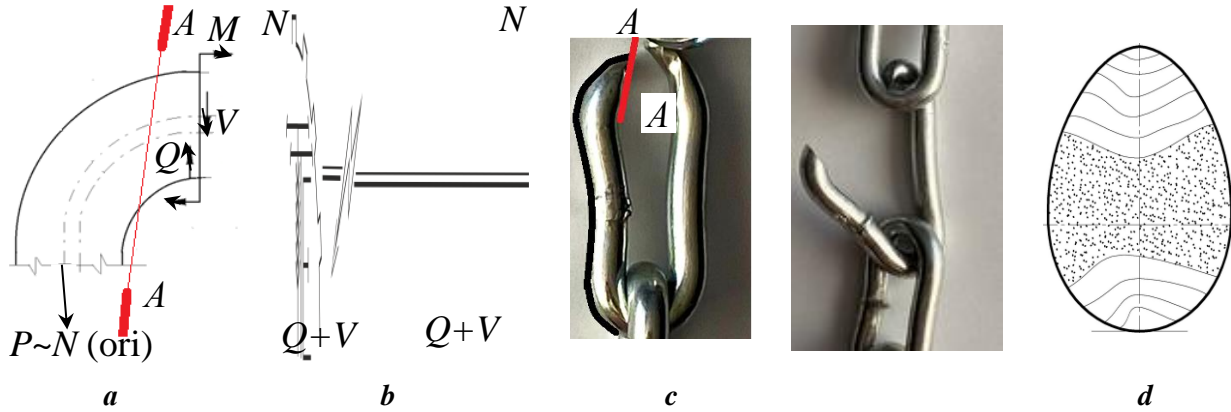


Fig. 5. Visual cognitive model:

$A - A$  – the considered cross-section of the arc of the link, which is defined as arbitrary  $\alpha$ ,  $P$  – chain tensile force,  $N$  – longitudinal force in the cross-section under consideration  $A - A$ , which depends on the orientation angle  $\alpha$  of the cross-section under consideration  $A - A$ ,  $Q$  – force in the contact zone of adjacent links,  $V$  – transverse force,  $M$  – bending moment,  $\sigma_N$  – normal stresses from force  $N$ ,  $\sigma_M$  – normal stresses from moment action  $M$ ,  $\sigma_{\Sigma}$  – total normal stresses,  $\tau_Q$  – tangential stresses from the action of a force  $Q$ ,  $\tau_V$  – tangential stresses from the action of a transverse force  $V$ ,  $\tau_{\Sigma}$  – total tangential stresses,  $\tau_{max} \approx 0,31q_{max}$  – maximum tangential stresses,  $q_{max}$  – maximum specific pressure in the contact area of the links

Ultimately, the combination of these internal force factors leads to the stochastic emergence of some dangerous cross section. *A – A* (Fig. 6-a) arc of a link of a round-link cargo chain, in which the processes of formation of microcracks of detachment and longitudinal shear are combined. In this case, the mouths of both cracks move in the opposite direction (Fig. 6-b), which ultimately leads to brittle fracture of the bridge between the opposing cracks (Fig. 6-c, 6-d).



**Fig. 6. The nature of the chain link failure:**

*a – dangerous section A-A of the arc of the chain link, b – stochastic formation of common cracks, the mouths of which move towards each other, c – the nature of the chain link fracture in the A-A cross-section plane, d – the nature of the link fracture surface;*

*A-A – dangerous cross-section of the arc of the chain link, P~Nori – longitudinal force N – which is defined as a stochastically oriented component of the force P, Q – force in the contact zone of adjacent links, V – transverse force, M – bending moment*

The results of experimental studies of the force characteristics of the stressed state of the links of round-link cargo chains are in Table 2.

**Table 2.**  
**Results of experimental studies of the force characteristics of the stressed state of the links of round-link cargo chains**

| Caliber | Link characteristics | Number of links in the sample | Destruction effort, 2N, кН | Cross-sectional area of the link (two arms), m <sup>2</sup> | Destructive stress, МПа |
|---------|----------------------|-------------------------------|----------------------------|---|-------------------------|
| 3       | Short                | 5                             | 10,6                       | 1,414×10 <sup>-5</sup>                                      | 749,6                   |
|         | Long                 |                               | 11,6                       |   | 820,4                   |
| 4       | Short                |                               | 14,1                       | 2,512×10 <sup>-5</sup>                                      | 561,3                   |
|         | Long                 |                               | 15,2                       |   | 605,3                   |
| 5       | Short                |                               | 21,2                       | 3,926×10 <sup>-5</sup>                                      | 540,0                   |
|         | Long                 |                               | 22,0                       |   | 560,3                   |
| 6       | Short                |                               | 28,4                       | 5,652×10 <sup>-5</sup>                                      | 502,5                   |
|         | Long                 |                               | 29,3                       |   | 517,5                   |
| 8       | Short                |                               | 49,2                       | 10,048×10 <sup>-5</sup>                                     | 489,6                   |
|         | Long                 |                               | 51,7                       |   | 514,5                   |

According to the results of verbal analysis of experimental data of destructive stress  $\sigma_{\Sigma}$  links of round-link cargo chains, the dynamic nature of the change has been established  $\sigma_{\Sigma}$  (function) with increasing caliber value  $k$  (argument) of the chain. Considering that the analytical model of the specified functional connection is characterized not only by a certain “saturation” of the argument, but also has a clear lower limit, the most appropriate variant of the “structural architecture” of such a model will have the form:

$$\sigma_{\Sigma}(k) = A + \text{Barcsch}(C_k) \quad (1)$$

where

$$\text{arcsch}(k) = \ln \ln \left( \frac{1}{k} + \sqrt{\frac{1}{k^2} + 1} \right) \quad (2)$$

Based on the least squares method, we determine an analytical model of the dependence of the destructive stress  $\sigma_{\Sigma}$  links of round-link cargo chains from the caliber value  $k$  chains (Fig. 7):

$$\sigma_{\Sigma}(k) = 470 + 420 \cdot \operatorname{arcsch}(0,85 \cdot k) \tag{3}$$

To verify the adequacy of the developed analytical model, a comparison of experimental research data and corresponding values was performed.  $\sigma_{\Sigma}$  obtained on the basis of their analytical definition according to equation (3). Data for comparison are given in Table 3. It was established that the level of confidence probability for the proposed analytical model is no worse than  $R_{\sigma} = 0,96$ .

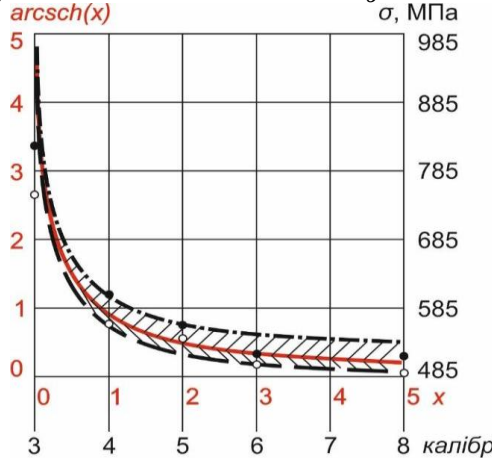


Fig. 7. Analytical model of the dependence of the destructive stress  $\sigma_{\Sigma}$  links of round-link cargo chains from the value of the chain gauge  $k$

Table 3.  
Data for comparing experimental data and corresponding values  $\sigma_{\Sigma}$  obtained on the basis of their analytical determination

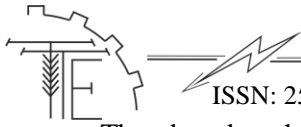
| Caliber $k$                                 | 3             | 4             | 5             | 6             | 8             |
|---|---------------|---------------|---------------|---------------|---------------|
| Experimentally determined $\sigma_{\Sigma}$ | 749,6         | 561,3         | 540,0         | 502,5         | 489,6         |
| Model values $\sigma_{\Sigma}$              | 820,4         | 605,3         | 560,3         | 517,5         | 514,5         |
|   | $\approx 790$ | $\approx 612$ | $\approx 556$ | $\approx 520$ | $\approx 495$ |

According to the results of the graphical analysis (Fig. 7) of the analytical model (3), it was established that the value of the additive component of the model is the basic normalized factor, the value of which for G80 chains according to the ASTM A391 standard is  $\approx 470$ . Then, the functional component of the considered model, which contains the inverse hyperbolic cosecant, determines the parameter of attenuation (reduction) of the value of the temporary resistance to fracture  $\sigma_T k$ , and the scale factor  $\langle 420 \rangle$  determines not only the mathematical sign of the intensity of the influence of the functional component on the overall modeling result, but also the physical “scale effect” of the chain link, as a separate detail. And finally, the value of the coefficient  $\langle 0.85 \rangle$  is an internal parameter of the model adaptation and determines the “sensitivity” of the model to variations in the chain caliber.

Thus, the proposed analytical model (3) comprehensively takes into account the combination of such factors on the magnitude of the destructive stress  $\sigma_{\Sigma}$  chain links:

- combination of external force factors: longitudinal force, bending moment, transverse force and normal compressive force in the contact zone of adjacent links;
- stress concentration in the “arc” zone of the link, the curvature of which is determined in particular by the gauge  $k$  of the chain, in contrast to the straight sections of the “shoulders” of the link;
- scale effect, the effect of which is manifested in a decrease in the mechanical strength characteristics of the link with an increase in the value of the chain gauge  $k$ ;
- Technological anisotropy, which is caused by the process of technological deformation of the bar (wire) of the link around the crossbar, leads to transverse anisotropy of the material layers in the section of the link arc and, as a consequence, to the formation of a network of separation cracks on the outer surfaces of the link.

For further analysis of the analytical model (3), we choose the value of  $\approx 470$  of the additive component for the invariant part (base level) of the fracture resistance  $\sigma_T$  chain. In this case, the local spike of the model in the form of its functional component is detected only for small calibers  $k \leq 3$ . Therefore, when determining the “sensitivity threshold” of destructive stress  $\sigma_{\Sigma}$  the local spike of the functional component of the model can be neglected.



Thus, based on the results of a comprehensive analysis of external force factors acting on a link of a cargo round-link chain, the scale effect, and the structural and technological differences in the manufacturing of the link, it is proposed to use a “sensitivity threshold” of destructive stress.  $\sigma_x$  instead of the value of the tensile strength of steel 20MnNiCrMo5-2. If we determine  $\sigma_x = \|\mathbb{470}\|$  (МПа), then when performing design calculations of the strength of G80 class cargo round link chains according to the ASTM A391 standard, made of 20MnNiCrMo5-2 steel, it is advisable to use general mechanical engineering standards for safety factors  $[n] = 1,5 \dots 2,5$ .

## 5. Conclusion

Based on a comprehensive analysis of the components of the stress state of the arc section of a cargo round-link chain, a visual cognitive model of this section was proposed, which determined the “structural architecture” of the analytical model of the dependence of the destructive stress of a round-link cargo chain on the value of its caliber.

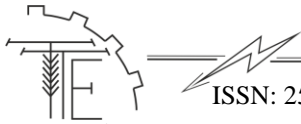
Based on the results of experimental studies of the strength characteristics of the stressed state of the links of round-link cargo chains, the “sensitivity threshold” of the destructive stress was determined, the value of which for class G80 chains according to the ASTM A391 standard, made of 20MnNiCrMo5-2 steel, was set as  $\|\mathbb{470}\|$  (MPa).

In the case of using the “sensitivity threshold” of the destructive stress instead of the value of the tensile strength of the material for the manufacture of cargo round-link chains, it is advisable to use general engineering standards for safety factors.

Further studies of the mechanical characteristics of cargo round-link chains should be aimed at universalizing the characteristics of their mechanical strength not only for chains manufactured according to the ASTM A391 standard, but also for a wider range of technical industrial chains.

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### АНАЛІЗ НАПРУЖЕНОГО СТАНУ ЛАНКИ ВАНТАЖНОГО ЛАНЦЮГА ЗА УМОВ СТАТИЧНОГО НАВАНТАЖЕННЯ

Універсалізація регламентованих показників коефіцієнтів запасу міцності для широкого спектра технічних промислових ланцюгів та наукове обґрунтування строку служби таких ланцюгів є важливим народногосподарським завданням. Метою даної роботи є дослідження напруженого стану ланок круглоланкових вантажних ланцюгів та обґрунтування пропозицій щодо вибору їх коефіцієнтів запасу міцності для використання в машинах і механізмах загального машинобудування. На основі комплексного аналізу складових напруженого стану дугової ділянки круглоланкового вантажного ланцюга, виконаного із застосуванням розробленої візуальної когнітивної моделі цієї ділянки, а також з урахуванням результатів експериментальних випробувань механічних характеристик круглоланкових ланцюгів калібрів 3, 4, 5, 6, 8 класу G80 відповідно до стандарту ASTM A391, виготовлених зі сталі 20MnNiCrMo5-2, встановлено «порог чутливості» руйнівного напруження ланки як альтернативу значенню границі міцності матеріалу, з якого виготовлені ланки ланцюга. При цьому рівень довірчої ймовірності отриманих результатів становить не менше 0,96. Запропоновано у випадку використання «порогу чутливості» руйнівного напруження замість значення границі міцності матеріалу для виготовлення круглоланкових вантажних ланцюгів застосовувати загальномашинобудівні нормативи коефіцієнтів запасу міцності, які знаходяться в межах 1,5...2,5. Визначено перспективи подальших досліджень, спрямованих на універсалізацію характеристик механічної міцності широкого спектра технічних промислових ланцюгів.

Запропонований аналітичний підхід забезпечує вдосконалення методів оцінювання міцності та оптимізацію коефіцієнтів запасу міцності вантажних круглоланкових ланцюгів, що використовуються у загальному машинобудуванні.

**Ключові слова:** круглоланковий вантажний ланцюг, напружений стан, коефіцієнт запасу міцності, візуальна когнітивна модель, механічні випробування, границя міцності, «порог чутливості» руйнівного напруження.

**Ф. 3. Рис. 7. Табл. 3. Літ. 16.**

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