The building structures’ bearing capacity assessment with the nomogram method

N V Pirumyan*, M G Stakyan
National University of Architecture and Construction of Armenia, 105, Teryan Street, Yerevan, 0009, Republic of Armenia

E-mail: pirumyannarine@gmail.com

Abstract. The complex assessments of the main jointly acting and heterogeneous factors (geometric parameters, stress concentration, surface hardening and compressive stresses) on the building structures elements and units’ fatigue resistance, which in early studies were taken into account in a differential way, are considered. In this paper, for the factors’ complex assessments, the method of prioritizing the choice of one of them, which is dictated by the requirements for building structures (design, technological, operational, technical maintenance, repair and restoration), is adopted. As a priority factor, in particular, the technology of surface hardening is considered, the use of which significantly increases the structural elements’ bearing capacity and allows the application of relatively cheap low - and medium-carbon structural steels as the main material. Using the method of system analysis, the classification and grouping of the parameters of these factors and fatigue resistance indicators was performed and their database was created. The statistical data processing was performed and the regression equations between the specified parameters and indicators were obtained. Using the principle of the priority of factors, systems, the obtained equations for applying the interrelated values of these indicators in calculations for the bearing capacity of structural elements are formed. Using the equations of the obtained systems in L...IV quadrants using the grid (x,y), considering the logical sequence of determining the fatigue resistance and the priority influencing factor’s principle, by means of the nomogram method three nomograms are composed, with the priority to the factors considered, which allow to determine the whole complex of these indicators promptly and taking into consideration the production environment by the simple graphical constructions means.

1. Introduction
The organization and further improvement of the production processes in the new conditions involves the systematical application of materials science, design, technological, assembling, operational, expert complex processes and technical maintenance processes, as well as the use of the interrelated technical characteristics; related optimal variants. Among these, according to the requirements, the processes of final completion of critical structural elements that provide the necessary performance indicators for working surfaces are highlighted. One of the relatively simple and effective methods of their optimization is to increase the surface plastic deformation (SPD) technological methods’ strength due to which the necessary micro-roughness of the working surfaces are formed, and in the presence of a deformed layer and compressive stresses, the strength and wear resistance of the elements are increasing [1-4].
The research in this direction mainly considered the implementation of the new technologies for strengthening in order to increase the bearing capacity of a certain class structures and units of technological equipment [5, 6]. The regularities of strengthening phenomena in surface layers, as well as corrosion, friction, and fatigue effects, have been relatively scarcely studied [7-10].

2. Methods
The factors that influenced the operational reliability of machines can be grouped according to the following parameters: material science, structural, weighing, technological, physical- mechanical condition of the strong layer, fatigue endurances, wear-resistance, corrosion resistance, electrical and electronic safety.

Comprehensive monitoring of these activities in various combinations, as well as taking priority one of them determines the mathematical simulation of these processes and optimization of the observed activities' indicators. These indicators are the parameters of the $\Delta h, d, \bar{a}_\alpha$ influencing factors and $K_{da}, K_\sigma, K_{\sigma d}, K_{RD}$ are the coefficients, which are the endurance limits ratio that characterizes the initial state, and the influencing factor in fatigue processes, and $\bar{\sigma}_R$ is the limit of the median endurance, which takes into account all these coefficients. These subgroups of parameters are included in one common multiparametric function, which is an integral mathematical model of the problem in question [11-13]:

$$\Phi_0[(\Delta h, d, \bar{a}_\alpha), (K_{da}, K_\sigma, K_{\sigma d}, K_{RD}, \bar{\sigma}_R(\alpha))] = 0. \quad (1)$$

(1) can be represented as two separate groups of multiparametric functions, for each of which a separate system of parametric equations can be formed:

a) individual dependencies $K_{da}, K_\sigma, K_{\sigma d}, \bar{\sigma}_R$ on $\Delta h, d, \bar{a}_\alpha$, depending on the influencing factors,
b) related dependencies of the same values on $\Delta h, d, \bar{a}_\alpha$.

Possible options for prioritizing the existing factors for the case (a) are:

1. $(\Delta h, d, \bar{a}_\alpha)$,  3. $(d, \Delta h, \bar{a}_\alpha)$,  5. $(\bar{a}_\alpha, \Delta h, d)$,
2. $(\Delta h, \bar{a}_\alpha, d)$,  4. $(d, \bar{a}_\alpha, \Delta h)$,  6. $(\bar{a}_\alpha, d, \Delta h)$. \quad (2)

Only options 1, 3 and 5 of these 6 options, were considered, they are of practical interest. As a result, three groups of functions, that meet the quantitative assessment of the hardening results for the structural elements of any shape and size, are obtained:

| I | II | III |
|---|---|---|
| $K_{da} = f_1(\Delta h, d, \bar{a}_\alpha)$ | $K_{da} = \varphi_1(d, \Delta h, \bar{a}_\alpha)$ | $K_{da} = \psi_1(\bar{a}_\alpha, \Delta h, d)$ |
| $K_\sigma = f_2(\Delta h, d, \bar{a}_\alpha)$ | $K_\sigma = \varphi_2(d, \Delta h, \bar{a}_\alpha)$ | $K_\sigma = \psi_2(\bar{a}_\alpha, \Delta h, d)$ |
| $K_{\sigma d} = f_3(\Delta h, d, \bar{a}_\alpha)$ | $K_{\sigma d} = \varphi_3(d, \Delta h, \bar{a}_\alpha)$ | $K_{\sigma d} = \psi_3(\bar{a}_\alpha, \Delta h, d)$ |
| $K_{RD} = f_4(\Delta h, d, \bar{a}_\alpha)$ | $K_{RD} = \varphi_4(d, \Delta h, \bar{a}_\alpha)$ | $K_{RD} = \psi_4(\bar{a}_\alpha, \Delta h, d)$ |
| $\bar{\sigma}_R = f_5(\Delta h, d, \bar{a}_\alpha)$ | $\bar{\sigma}_R = \varphi_5(d, \Delta h, \bar{a}_\alpha)$ | $\bar{\sigma}_R = \psi_5(\bar{a}_\alpha, \Delta h, d)$ |

$(x = \Delta h)$, $(x = d)$, $(x = \bar{a}_\alpha)$.

The systems (3) allow the quantitative assessment of each specific case, taking into account the prevailing factor of practical interest.

The systems IV, V, VI for the case (b) are formed in two steps: first, the functional relationships of $K_{da}, K_\sigma, K_{\sigma d}$ indicators and $\bar{\sigma}_R$ as the arguments from the priority factors values $\Delta h, d, \bar{a}_\alpha$ that influence the structures are considered, and second - the arguments are replaced, and in subsequent functional relationships the coefficients $K_\sigma$ and $K_{\sigma d}$ are taken as the priority factors, and $\Delta h, d, \bar{a}_\alpha$ in these relationships already acts as the functions parameters.

For the observed cases in (3), the new systems will have the following form:

IV
V
1. \( K_{d\sigma} = f_1(\Delta h, d, \bar{\alpha}_\sigma), \quad x = \Delta h, \)
2. \( K_{d\sigma} = f_2(K_{\sigma}, \Delta h, d, \bar{\alpha}_\sigma), \quad x = K_{\sigma}, \)
3. \( K_{v\sigma} = f_3(K_{\sigma}, \Delta h, d, \bar{\alpha}_\sigma), \quad x = K_{\sigma}, \)
4. \( K_{v\sigma} = f_4(K_{\sigma D}, \Delta h, d, \bar{\alpha}_\sigma), \quad x = K_{\sigma D}, \)
5. \( \bar{\sigma}_R = f_5(K_{\sigma D}, \Delta h, d, \bar{\alpha}_\sigma), \quad x = K_{\sigma D}, \)
6. \( K_{d\sigma} = \varphi_1(d, \Delta h, \bar{\alpha}_\sigma), \quad x = d, \)
7. \( K_{d\sigma} = \Phi_2(K_{\sigma}, d, \Delta h, \bar{\alpha}_\sigma), \quad x = K_{\sigma}, \)
8. \( K_{v\sigma} = \Phi_3(K_{\sigma}, d, \Delta h, \bar{\alpha}_\sigma), \quad x = K_{\sigma}, \)
9. \( K_{v\sigma} = \Phi_4(K_{\sigma D}, d, \Delta h, \bar{\alpha}_\sigma), \quad x = K_{\sigma D}. \)

A database is compiled with the classification of the values \( \Delta h, d, \bar{\alpha}_\sigma \) and their corresponding coefficients \( \bar{\sigma}_R \) and \( K_{d\sigma}, K_{\sigma}, K_{v\sigma}, K_{\sigma D} \), using the standard software packages, parametric regression equations are obtained that are used in calculation processes to define the optimal values of indicators \( K_{d\sigma}, K_{\sigma}, K_{v\sigma}, K_{\sigma D} \) \([11 - 13]\).

Another important feature of the systems’ application (4) is the graphical method for determining these indicators: application of the nomogram method for representing these systems allows to represent the functions of the system in quadrants I ... IV, in the coordinate system \((x, y)\).

3. Results

The primary factors that are influencing on the problem in question are the accounting values: the main geometric parameters \((d, l)\) of the elements and units of the designed and manufactured technical system and associated with the configuration of the stress accumulation edge \((\bar{\alpha}_\sigma)\), the data of the work surfaces’ hardened layer \((\Delta h, HV_{\text{max}})\), which forms the primary subgroup composition of these values.

To estimate the calculation values of these parameters, regression equations were obtained in the form of the power functions of 1...3 order \((R^2 > 0.9)\). Since the main problem in this paper is the quantitative assessment of hardening under the combined impact of various factors, the calculation points associated with the parametric functions (4) are represented with the notations o, o, +, and x (figures 1-3), which correspond to the values of the main factor = 0, 0.05, 0.10 and 0.15 \(mm\).

Considering the variety of regression equations obtained (192 units) and the combinations of various parameters included in them, for all the functions (4), these equations are numbered \((N 1, \cdots, N 16)\) and presented in nomograms, in accordance with the functions \(1...5, 6...10\) and \(11...15\) of (4) (Figures 1-3) \([11-13]\).
Figure 1. The nomogram of the functions group 1,..., 5 of system IV of (4). The curves N1,..., N16 correspond to 16 types of each of the specified group’s functions, in accordance with $d$ and $\bar{\sigma}$. 

Figure 2. Nomogram of the function group 6, ... 10 of the system V of (4). The curves N1,..., N16 correspond to 16 types of each of the specified group’s functions according to $\Delta h$ and $\bar{\sigma}$. 
Figure 3. Nomogram of the function group 11, ..., 15 of the system VI of (4). The curves N1, ..., N16 correspond to 16 types of each of the specified group’s functions, in d and Δh.

The parametric functions’ gradients 1, ... 15 of (4) actually characterize the primary factor (monotonous or variable) influence nature and specify the indicators’ ranges that will allow the structural elements’ bearing capacity assessment to apply the specific or alternative solutions [14].

The impact of the surface hardening factor led to a monotonous change in most of the functional connections of the system IV (Figures 1. I, III, and IV quadrants). This is especially evident in the III and IV quadrants, where the $K_{d\sigma}, K_{dD}$ and $\sigma_R$ functions are presented, which ultimately form a positive influence of the strengthening factor on the fatigue resistance indicators. At $\bar{\sigma}_a \leq 1.7$ values, the hardening completely eliminates the stress accumulation factor, which is the main advantage of surface hardening.

When the geometric factor is primary (Figure 1. System V), the similar changes in indicators are also presented, but with the difference, that in the II and III quadrants, functional dependencies are close to linear and relatively constant values of fatigue resistance, the coefficients are presented in the intervals of changes in the secondary parameters of these functions. In this case, the functional curves’ classes of the I quadrant $K_{d\sigma} = \varphi_1(d, \Delta h, \bar{\sigma}_a)$ are arranged regularly and identically, which is due to a relatively smooth and monotonous change in the $\bar{\sigma}_R$ values that characterize the coefficient in the selected interval of the geometric parameter (d).

When the stress accumulation factor ($\bar{\sigma}_a$) is primary (priority) in system VI (Figure 3) the arrangement and nature of changes in the functional curves’ classes is specific, which characterizes the significant influence of this factor on the values of $\bar{\sigma}_R$. In this case, the functional relationships show the underlined variable gradients and are cyclical, and at $\bar{\sigma}_a \geq 2.75$ - the phenomenon of weakening the surface hardening effectiveness appears as a secondary factor. This makes it necessary to use in the process of the structures’ designing and manufacturing, the $K_{d\sigma}, K_{\sigma}, K_{o\sigma}, K_{oD}$ coefficients and $\bar{\sigma}_R$ endurance limits can be calculated from the extreme values.

In the IV quadrant, the function curves ($K_{dD}, \bar{\sigma}_R$) are distributed, they actually complete the complex influence of these factor on the structural elements’ bearing capacity. In contrast to the other functions of systems IV, V, VI, in this case, regardless of the influencing factors’ priority principle, the changes of functions ($K_{dD}, \bar{\sigma}_R$) in the systems IV, V, VI are identical: they are located as much as possible in a narrow space of curves along the same monotonous gradient, in the systems IV, V they
practically coincide and only in the system VI the curves’ class in the range of $K_d = 0.75 \ldots 200$ is distributed relatively low (the gradient is small), which is reflected in the rising of the stress accumulation factor’s influence at $\bar{a}_\sigma \geq 2$.

Summary
Unlike the principle of differential assessment of influencing factors, the proposed nomogram method allows to carry out a comprehensive and simultaneous assessment of various influencing factors, to choose the optimal intervals of their parameters (coefficients), and to solve the following common problems [15-18]:
- to perform the optimal actions for strengthening the overloaded components and elements in the working area in accordance with the operating modes of the designed structure;
- to indicate the reasonable service life of the structure and technical indicators that ensure normal working conditions;
- to solve the basic tasks of a direct and reverse nature in the design, production and operation of the structures by using surface hardening and to ensure economic efficiency;
- to create a structures that will provide high reliability and safe operation during its service life and will have reasonable technical maintenance and repair schedules, considering the incompatible requirements for the designed structure (high operating speeds, productivity, energy stability and contemporary control means and at the same time low material consumption, low cost and process automation).

References
[1] Papshev D D 1978 Finishing and strengthening treatment with surface plastic deformation Mechanical Engineering (Moscow).
[2] Oleynik N V 1985 Bearing capacity of the structural elements under cyclic loading (Kiev, Naukova Dumka).
[3] Gubanov V F et al. 2008 Roller burnishing finishing technology Repair, restoration, modernization 11 36-38.
[4] Nezhinsky A M 2007 Improving the technology of surface treatment of machine parts by methods of surface-plastic deformation Mechanical engineering 10 13-22.
[5] Barats Ya I, Milovanova L R 2006 Processing of hole surfaces by surface-plastic deformation with the formation of a regular microrelief Metalworking 3 28-34.
[6] Pachurin G V, Gushchin A N 2007 Increasing the operational durability of metal products by technological methods The machine construction bulletin [Russian Engineering Research] 6 62-65.
[7] Sosnovsky L A 1987 Statistical mechanics of fatigue failure (Science and technology, Minsk).
[8] Ahrens U, Besserdieh G, Maier H J 2000 Effect of stress on the bainitic and martensitic phase transformation behavior of a low alloy tool steel Adv. Mech. Behav. Plast Damage, Amsterdam, Elsevier 2 817-822
[9] Matvienko Yu G 2006 Models and criteria of fracture mechanics (FIZMATLIT, Moscow).
[10] Pirumyan N, Stakyan M 2019 Assessment of corrosion fatigue strength of gas-transport system constructions under atmospheric forcing IOP Conf. Se.: Materials Sci.Eng. 698 022077.
[11] Pirumyan N, Stakyan M, Galstyan G 2020 Mathematical Modeling of the Test Process of Construction Materials Key Engineering Materials 828 115–120. https://doi.org/10.4028/www.scientific.net/kem.828.115
[12] Pirumyan N, Stakyan M, Galstyan G 2020 Software Processing of the Test Results of Building Materials Key Engineering Materials 828 121–128. https://doi.org/10.4028/www.scientific.net/kem.828.121
[13] Pirumyan N, Stakyan M 2019 Mathematical model of pressure distribution in the main gas-transport system IOP Conf. Se.: Materials Sci. Eng. 698 066022.
[14] Pirumyan N, Stakyan M 2019 Bearing capacity of elements of a gas transportation system E3S Web of Conferences, FORM-2019 97 04027 pp 1-9. https://doi.org/10.1051/e3sconf/20199704027

[15] Gaiduk V V, Volodin V L 2002 Research of resistance to fatigue destruction of metals after impulse actions The higher educational herald. Ferrous metallurgy 2 18-22.

[16] Butenko V I et al. 2005 Opportunities and prospects for finishing and strengthening processing of parts with a multi-contact vibro-impact tool Izv. SFU. Techn. Sciences 9 (53) 146.

[17] Kirpichev V A et al. 2008 Prediction of fatigue resistance of hardened parts with different stress concentrators Mathematical modeling and boundary value problems: Tr. V Vseross. Conf. with int. Uch. CH. 1, Samara 143-147.

[18] Bhadeshia H K, Francis J A, Stone H J 2007 Transformation plasticity in steel weld metals Proc. of 10th Int. Aachen Welding Conf. 22-25.

Acknowledgements
This work has been carried out in the frame of the “Creating the ways for sustainable urban, architectural and construction complexes development in Republic of Armenia and elaboration of directions with use of permanent monitoring system” program, financed by the Science Committee of Republic of Armenia.