Materials Physics and Mechanics. 2023;51(7): 117-123
Research article
http://dx.doi.org/10.18149/MPM.5172023_10

Submitted: September 25, 2023
Approved: October 24, 2023
Accepted: December 4, 2023

Stiffness characteristics of implanted steel plates after exposure to corrosion

R.R. Giniyatullin [1] ✉, N.M. Yakupov [1], V.G. Kuznetsov [2]

[1] Institute of Mechanics and Engineering, Kazan Science Center, Russian Academy of Sciences, Kazan, Russia

[2] Institute for Problems of Mechanical Engineering RAS, St. Petersburg, Russian Federation

✉ true_way@mail.ru

Abstract. Ensuring the safety of structures from corrosion damage is an important task. One of the promising directions for increasing corrosion resistance is modifying the surface layer of a structural element using the ion implantation method. The standard approach of uniaxial tension for assessing the mechanical properties of thin-walled elements with corrosion defects is also ineffective, and the gravimetric method does not take into account changes in the structure of the material and physical and mechanical characteristics caused by loosening the material to a certain depth. In this work, on the basis of the experimental-theoretical method, the integral mechanical characteristics of the samples after exposure to corrosion were determined. The effectiveness of protecting steel samples from corrosion by pre-treatment of the surface layer with ion implantation has been demonstrated. The results of an experimental study of corrosive wear of a thin-walled sheet steel plate, on the surface layer of which carbon ions were implanted, are presented.
Keywords: ion implantation; surface layer; experimental-theoretical method; corrosion wear; reduced modulus of elasticity; tensile rigidity

Citation: Giniyatullin RR, Yakupov NM, Kuznetsov VG. Stiffness characteristics of implanted steel plates after exposure to corrosion. *Materials Physics and Mechanics*. 2023;51(7): 117-123. DOI: 10.18149/MPM.5172023_10.

Introduction

The structure of the material of structural elements largely determines their properties. In this case, the structure and properties of the surface layer are of particular importance. In metal elements, the morphology, phase composition and dislocation structure of the surface layers determine wear resistance, endurance limit, heat resistance and other characteristics. Of great interest is the method of ion implantation, which makes it possible to introduce a dosed amount of ions of almost any element into a metal without changing the boundaries of its grains.

In the 70s - 80s of the twentieth century, along with traditional methods of volumetric impact on metal materials, such as thermomechanical processing, hardening, shock wave loading and other methods, it became possible to carry out surface treatment with concentrated energy flows (from 10^3 to 10^8 W/cm^2) [1–4], using electron and ion beams, laser radiation and plasma flows.

When processing with concentrated energy flows, radiation, thermal and shock-mechanical effects are simultaneously carried out. The processes of structural restructuring that develop during this process make it possible to obtain surface layers with a unique set of physical and mechanical properties.

Publisher: Peter the Great St. Petersburg Polytechnic University

The use of laser radiation to improve the performance properties of materials is well reflected in monographs and reference books, in particular in works [1,5]. The work [6] presents the structures of various types of steel subjected to laser heating.

Compared with laser radiation, processing with electron and ion beams has a number of advantages: higher efficiency, lower cost per unit of energy, the ability to process large areas, as well as a high degree of absorption of the supplied energy by all materials. When processing solids with electron and ion beams for the purpose of their modification, low-energy, high-energy and powerful ion beams are used.

Speaking about the advantages of the ion implantation method, we can note the possibility of controlling the number of introduced impurity atoms by simple integration of the ion current, the purity of the technology, and others.

Unfortunately, the ion implantation method also has disadvantages - bombardment with heavy particles leads to the formation of defects on the surface, and the method is also relatively expensive.

Intensive research into ion implantation in metals may have begun with the work of Trillat and Heimann [7] and the experiments of Crowder and Ta in [8]. A natural method of increasing the corrosion resistance of a metal surface is the implantation of ions, which, as alloying additives, can prevent or reduce the development of metal corrosion, for example, nickel or chromium ions in steel.

Many works are devoted to the study of changes in the mechanical properties of metal surfaces. An increase in the microhardness of steel was observed after implantation of nitrogen, argon, boron and carbon ions [9]. When implanting nitrogen ions, the microhardness of steel increases according to Vickers from 300 to 400 kg [10].

The effect of the introduction of titanium-nickel and chromium-nickel ions into the surface layer of structural steel VSt3sp is shown in [11]. After implantation of chromium-nickel atoms, an increase in the wear resistance of steel up to 2.5 times was observed.

Microhardness and corrosion resistance studies have been conducted on the effect of nitrogen ion implantation on 7075 aluminum alloy [12]. Potentiodynamic corrosion tests were carried out in NaCl solution. The results showed that the microhardness increased by 90.81% after implantation. Corrosion testing showed an improvement in corrosion resistance by reducing the corrosion rate by a factor of 3.

A decrease in the corrosion rate by 1.78 times was recorded with two-stage implantation of oxygen ions, as well as combined aluminum and boron ions [13]. Increased corrosion resistance is confirmed by long-term acid corrosion tests at pH 3.5 and accelerated electrochemical testing using a potentiostat .

To increase the corrosion resistance of ferritic-martensitic steel SIMP, the authors of article [14] studied the effect of implantation of silicon ions and preliminary oxidation of the surface. It was found that increasing the Si content on the surface did not improve the corrosion resistance performance. In contrast, the pre-oxidized sample demonstrated high corrosion resistance due to the presence of a thin oxide layer enriched in Cr.

The effect of implantation of calcium ions on the corrosion resistance of titanium is presented in [15]. The results of electrochemical studies show that calcium-ion implantation increases corrosion resistance, but only under stationary conditions; During anodic polarization, samples implanted with calcium ions undergo corrosion.

The authors of the article [16] achieved suppression of local corrosion by using immersion ion implantation of nitrogen plasma on the surface of austenitic, duplex, martensitic and ferritic stainless steels. Nitrided stainless steel has shown high hardness and high corrosion resistance.

The use of the method of surface treatment with cathode spots of a vacuum-arc discharge led to both an increase in resistance to thermal fatigue and an increase in corrosion resistance [17,18].

The purpose of this work is to evaluate, on the basis of the experimental-theoretical method [19,20], the effectiveness of protecting steel samples from corrosion by pre-treating the surface layer with ion implantation.

Methods

Specimens subject to corrosive wear are thin-walled elements with a complex structure. To study the mechanical characteristics, an experimental-theoretical method was used [19]. The method allows, in contrast to the standard uniaxial test and the indenter method, to more accurately determine the integral mechanical properties of thin-walled elements.

In the experimental-theoretical method, at the first stage, round-shaped samples are cut out from the thin-walled element under study. Then, the samples are fixed along the contour on a special installation and loaded with uniform pressure P. In the process of increasing pressure P, the shape of the dome being formed is monitored. In particular, for the top of the dome, data is taken for the graph pressure P - deflection N. At the theoretical stage, experimental data is processed using relationships obtained from the nonlinear theory of shells. In this case, the reduced (integral) characteristics of the samples are determined, for example, the reduced modulus of elasticity. The method captures the influence of surface defects on the integral properties of samples.

For an elastic membrane in the case of average bending, the elastic modulus *E* and the tensile-compression stiffness *B* are calculated using the formulas:

$$E = \frac{NPa(1-\nu^2)}{h}\left(\frac{a}{H}\right)^3, \quad (1)$$

$$B = NPa\left(\frac{a}{H}\right)^3, D = B\frac{h^2}{12}, \quad (2)$$

where the values of the coefficients *N* are shown in Table 1; *P* is the uniformly distributed pressure; ν is the Poisson's ratio of the material; *h* is the current membrane thickness; *a* is the radius of the membrane; *H* is the current dome lift height (maximum deflection).

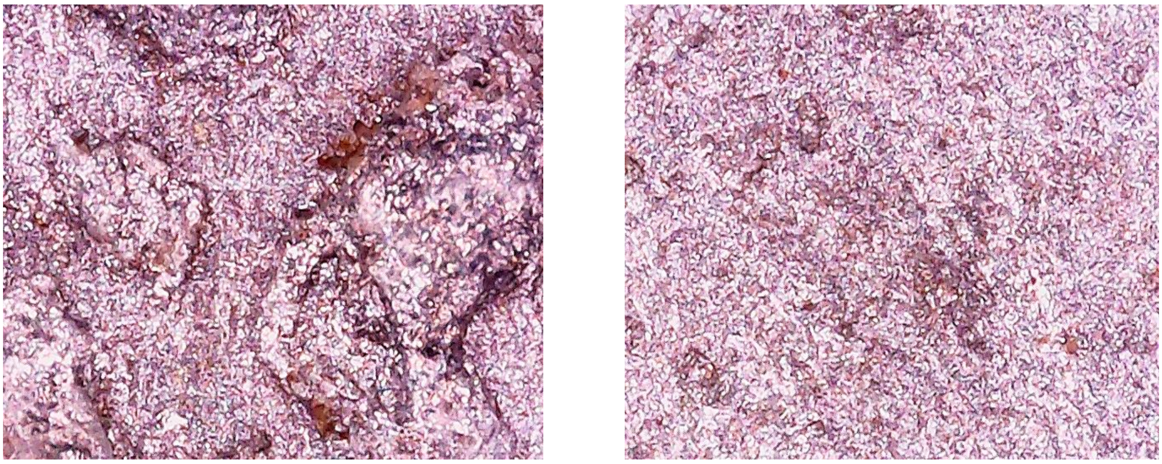
Table 1. Values of coefficients *N*

ν	0.25	0.3	0.4	0.5
N	0.311481993	0.303670085	0.290157232	0.279052533

Results and Discussion

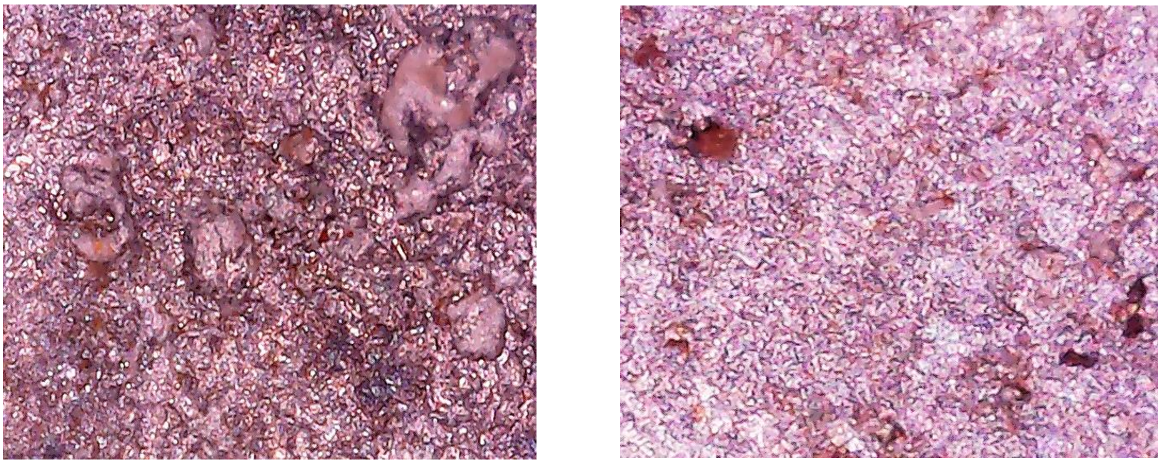
Corrosive wear tests were carried out on three pairs of metal samples made of sheet steel grade Steel 3 with a thickness of t = 0.5 mm. The surfaces of the samples were subjected to pulsed ion implantation with carbon C atoms. For implantation, a TEMP pulsed ion accelerator was used, with an atomic voltage of 280 keV (the number of pulses was 8). The samples were kept in an aggressive environment (10% hydrochloric acid - HCl): group No. 1 - two days, group No. 2 - three days, group No. 3 - four days. In each group of samples, a control "clean" sample that was not subjected to ion treatment was located next to its pair.

Figures 1-3 show images of the surfaces of samples of groups No. 1-3 after keeping them in an aggressive environment. The images are enlarged 400x, with samples without implantation on the left and samples with implantation on the right. The results of measuring the thickness of samples after exposure to an aggressive environment are presented in Table 2. From Fig. 1-3 it is clear that the surfaces of non-implanted samples have deeper corrosion cavities with larger dimensions in plan. This is obviously due to the fact that when carbon atoms are implanted into the surface layer of steel, the surface layer becomes compacted, the bonds of the crystal lattice are strengthened, and its chemical composition also changes. All this helps to increase chemical resistance when exposed to aggressive environments.



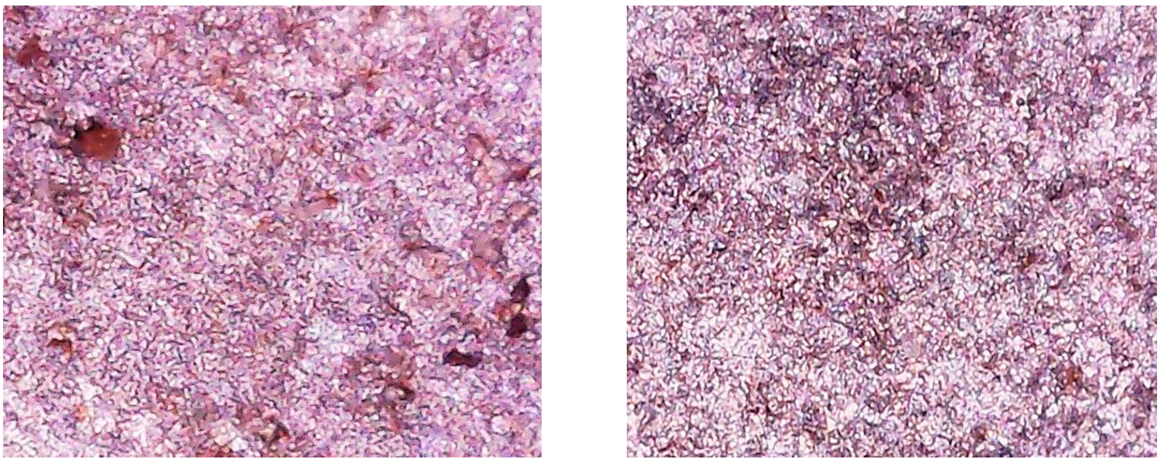
(a) (b)

Fig. 1. Samples of the 1st group: (a) not implanted, (b) implanted



(a) (b)

Fig. 2. Samples of the 2nd group: (a) not implanted, (b) implanted



(a) (b)

Fig. 3. Samples of the 3rd group: (a) not implanted, (b) implanted

Table 2. Experimental data

Group samples	Group No. 1		Group No. 2		Group No. 3	
Wear time, days	2		3		4	
Implantation	Yes	No	Yes	No	Yes	No
Thickness after wear, mm	0.481	0.469	0.478	0.464	0.468	0.452

Table 2 also shows that the thicknesses of samples subjected to ion implantation for all groups are slightly greater than for non-implanted samples. All this indicates that the implanted samples are more corrosion resistant.

Dependencies pressure *P* - bending rigidity *D* for the studied samples are presented in Tables 3 - 5. In the tables, samples previously subjected to ion implantation are designated as D_+ , and those not treated with ion implantation are designated as *D* -. Stress curves "bending rigidity *D* - pressure *P*" are presented in Figs. 4-6. The graphs show two curves: for a sample subject to and not subject to ion implantation. As can be seen from Fig. 4-6, the bending rigidity of the implanted samples are more than those of the samples not subject to ion implantation. This means that the implanted samples are more corrosion-resistant, that is, the effect of implantation is obvious.

Table 3. Dependence "pressure *P* - bending rigidity *D*" for sample of group No. 1

P, MPa	0.06	0.08	0.10	0.12	0.16	0.20
D_+, kg/cm^3	36.15	31.45	29.37	27.02	24.06	21.07
D_-, kg/cm^3	18.76	17.57	17.17	17.15	16.34	15.10

Table 4. Dependence "pressure *P* - bending rigidity *D*" for sample group No. 2

R, MPa	0.06	0.08	0.10	0.12	0.16	0.20
D_+, kg/cm^3	23.0	21.1	19.8	18.7	16.6	14.5
D_-, kg/cm^3	17.4	16.7	15.6	14.9	13.8	12.4

Table 5. Dependence "pressure *P* - bending rigidity *D*" for sample group No. 3

P, MPa	0.06	0.08	0.10	0.12	0.16	0.20
$\boldsymbol{D}_+$, kg/cm^3	21.3	18.2	15.9	14.7	12.8	11.2
$\boldsymbol{D}_-$, kg/cm^3	13.6	12.5	11.5	10.7	9.4	8.2

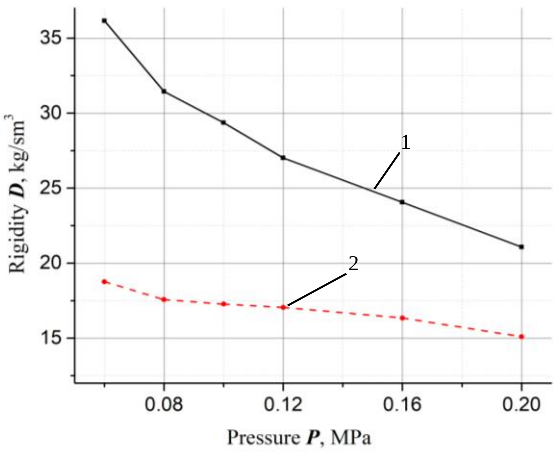


Fig. 4. Dependence "bending rigidity ***D*** – pressure ***P***" for group of samples No. 1: curve 1 – implanted samples; curve 2 – non-implanted samples

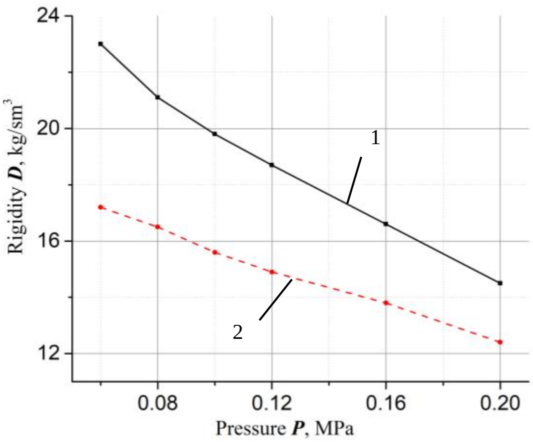


Fig. 5. Dependence "bending rigidity ***D*** – pressure ***P***" for group of samples No. 2: curve 1 – implanted samples; curve 2 – non-implanted samples

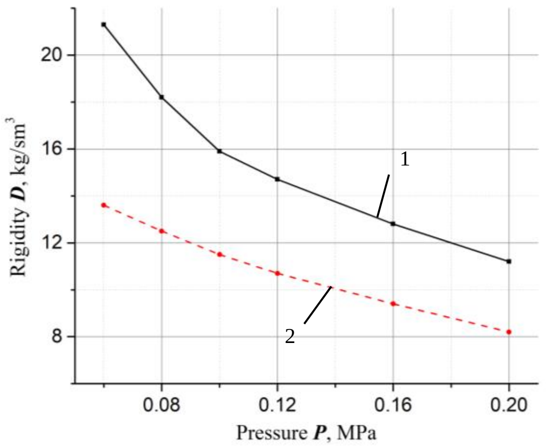


Fig. 6. Dependence "bending rigidity ***D*** – pressure ***P***" for group of samples No. 3: curve 1 – implanted samples; curve 2 – non-implanted samples

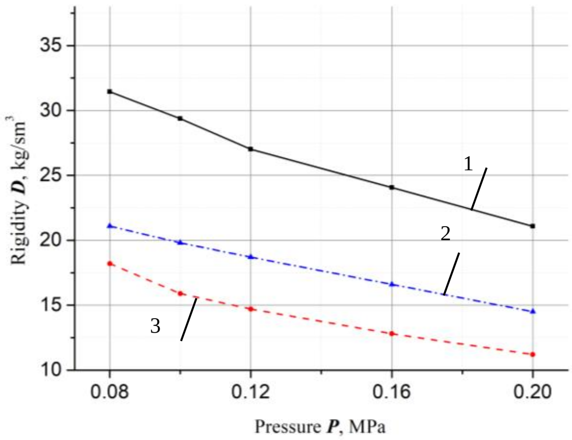


Fig. 7. Dependence "bending rigidity ***D*** – pressure ***P***" for implanted samples: curve 1 - 2 days; curve 2 - 3 days; curve 3 - 4 days

Figure 7 shows the "bending rigidity ***D*** - pressure ***P***" curves for implanted samples depending on the duration of exposure in an aggressive environment. As can be seen from Fig. 7, with increasing exposure time in an aggressive environment, the degree of corrosive wear increases.

Conclusion

Surface treatment of samples by ion implantation allows maintaining a passivating protective layer and, thereby, helps reduce corrosive wear. Despite the effectiveness of ion implantation treatment, with increasing exposure time in an aggressive environment, the effect of surface protection by ion implantation decreases. This in turn leads to corrosive wear and deterioration of mechanical characteristics. This was investigated using the experimental-theoretical method. Ion implantation is one of the effective ways to protect against corrosive wear.

References

1. Misaelides P. *Application of particle and laser beams in materials technology*. Dordrecht: Kluwer Academic Publishes; 1994.
2. Uglov AA, Selishchev SV. Boundary large-scale structures under the effect of concentrated energy-flow on metals. *Zhurnal Tekhnicheskoi Fiziki*. 1985;55(4): 649–654. (In-Russian)
3. Takagi T, Yamada I, Kimura H. *Ion Implantation in Semiconductors*. New York; 1970.
4. Hartley NE. *Application of Ion Beams to Materials*. Institute of Physics; 1975.
5. Rykalin NN, Uglov AA, Kokora AN. *Laser processing of materials*. Moscow: Mechanical Engineering; 1975. (In-Russian)
6. Sadovsky VD, Schastlivtsev VM, Tabatchikova TI, Yakovleva IL. *Laser heating and steel structure: Atlas of microstructures*. Sverdlovsk: Ural Branch of the Academy of Sciences of the USSR; 1989. (In-Russian)
7. Trillat JJ, Haymann IN. *Le bombardement ionique. Theories et applications*. Paris; 1961.
8. Crowder BL, Tan SI. *IBM Technical Disclosure Bulletin 14*. 1971.
9. Pavlov AV, Pavlov PV, Zorin EI, Tetel'baum DI. *All Soviet Meeting on Ion Beam Physics*. Kiev; 1974.
10. Gabovich MD, Budernaya LD, Poritskii VY, Protsenko IM. *All Soviet Meeting on Ion Beam Physics*. Kiev; 1974.

11. Vasetskaya. Ion implantation as a way to improve the operating durability of fine-size steel tool. *Eastern-European journal of enterprise Technologies*. 2013;6(5): 7–11.
12. Hapsari S, Sujitno T, Ahmadi H, Suprapto, Rizky AA. Analysis of nitrogen ion implantation on the corrosion resistance and mechanical properties of aluminum alloy 7075. *J. Phys.: Conf. Ser*. 2020;1436: 012075.
13. Dorofeeva TI, Fedorischeva MV, Gubaidulina TA, Sergeev OV, Sungatulin AR, Sergeev VP. Investigation of Corrosion Properties and Composition of the Surface Formed on AISI 321 Stainless Steel by Ion Implantation. *Metals*. 2023;13(8): 1468.
14. Xu N, Wang Zh, Shen T, Li B, Li G, Li T, Wei W. The effects of Si-ion implantation and preoxidation on the corrosion behavior of a new steel SIMP in 550˚C lead-bismuth eutectic. To be published in *Materials and Corrosion*. [Preprint] 2023. Available from: doi.org/10.1002/maco.202313865
15. Krupa D, Baszkiewicz J, Kozubowski JA, Barcz A, Sobczak JW, Biliński A, Lewandowska-Szumieł MD, Rajchel B. Effect of calcium-ion implantation on the corrosion resistance and biocompatibility of titanium. *Biomaterials*. 2001;22(15): 2139–2151.
16. Luiz LA, Emanuely BC, Kurelo S, Biscaia de Souza G, de Andrade J, Bruno Marino ClEl. Effect of nitrogen plasma immersion ion implantation on the corrosion protection mechanisms of different stainless steels. *Materials Today*. 2021;28: 102655.
17. Kuznetsov VG. Vacuum-arc hardening of metals surface. *Journal of Physics: Conference Series*. 2019;1396; 012027.
18. Kuznetsov VG. Analysis of stresses and deformations in a hollow cylinder under the influence of internal pressure and of field of temperatures. *Journal of Advanced Research in Technical Science*. 2020;22: 16–21. (In-Russian)
19. Yakupov NM, Nurgaliev AR, Giniyatullin RR, Yakupov SN. Operation of Structures with Corrosive Wear. *Russian Engineering Research*. 2013;33(2): 69–73.
20. Yakupov NM, Yakupov SN. Diagnostics of thin-walled structures of complex geometry and structure. *Structural Mechanics of Engineering Constructions and Buildings*. 2021;17(6): 576–587.

THE AUTHORS

Giniyatullin R.R.
e-mail: true_way@mail.ru

Yakupov N.M.
e-mail: yzsrr@mail.ru

Kuznetsov V.G.
e-mail: kvgipme@gmail.com