

Diagnostics of Structures under Vibration Loads and Elevated Temperatures

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Abstract. Industrial building structures operate under severe conditions. An apt example of such structures are fan cooling towers, which resist significant vibration loads caused by a running fan; at the same time, the internal surfaces of the structures are exposed to relatively high temperatures from contact with cooled water, and the external surfaces are constantly exposed to the environment. The well-known approach to structural diagnostics does not take into account changes in the integral mechanical properties of thin-walled structural elements and the formation of local depressions and holes. Using the example of a large-sized fan cooling tower, an approach to diagnostics of structures affected by vibration from a running fan and the temperature of the cooled water, as well as the environment, is described. The effect of vibration and temperature on the process of corrosion wear of thin-walled structural elements has been studied experimentally and theoretically. Based on a new version of the finite element method developed for calculating structures in a cylindrical coordinate system, the initial and current state of the metal part of the fan cooling tower is investigated, taking into account plastic deformations. When analyzing the current state, corrosion defects and changes in the stiffness properties of thin-walled elements caused during operation as a result of the combined effects of vibration and relatively high temperatures were taken into account. It has been established that the presence of vibration and elevated ambient temperature contribute to accelerated corrosion; at the same time, the effect increases with increasing temperature and time of exposure to vibration. Corrosion wear leads to a significant increase in stresses and the formation of plastic deformations, which leads to a redistribution of stresses. It is noted that the discovered effects must be taken into account in the design and service of metal structures that experience significant vibration loads and operate at high temperatures.

Keywords: thin-walled structures, fan cooling tower, corrosion wear, experimental and theoretical method, mechanical properties, thin-walled elements, defects, high temperature, interpolation splines, finite element method variant, stress-strain state, elastic and plastic deformations

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Диагностика состояния конструкций в условиях вибрационных нагрузок и повышенных температур

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Аннотация. Промышленные строительные конструкции работают в тяжелых эксплуатационных условиях. Ярким примером таких конструкций являются вентиляторные градирни, которые воспринимают существенные вибрационные нагрузки, вызываемые от работающего вентилятора; при этом внутренние поверхности конструкций испытывают воздействие относительно высоких температур от контакта с охлаждаемой водой, а наружные поверхности находятся постоянно под воздействием окружающей среды. Известный подход диагностики конструкции не учитывает изменение интегральных механических свойств тонкостенных элементов конструкций и образование локальных углублений и сквозных отверстий. На примере крупногабаритной вентиляторной градирни описан подход диагностики конструкций, подверженных воздействию вибрации от работающего вентилятора и температуры охлаждаемой воды, а также окружающей среды. Экспериментально-теоретическим методом исследовано влияние вибрации и температуры на процесс коррозионного износа тонкостенных элементов конструкций. На базе нового варианта метода конечных элементов, развитого для расчета конструкций в цилиндрической системе координат, исследовано исходное и актуальное состояние металлической части вентиляторной градирни с учетом пластических деформаций. При расчете актуального состояния были учтены коррозионные дефекты и изменения жесткостных свойств тонкостенных элементов, возникших в процессе эксплуатации в результате комплексного воздействия вибрации и относительно высоких температур. Установлено, что наличие вибрации и повышенная температура среды способствуют ускоренной коррозии; при этом с увеличением температуры и времени воздействия вибрации эффект усиливается. Коррозионный износ приводит к существенному росту напряжений и образованию пластических деформаций, что обуславливает перераспределение напряжений. Отмечено, что обнаруженные эффекты необходимо учитывать при проектировании и эксплуатации металлических конструкций, испытывающих существенные вибрационные нагрузки и работающих при высоких температурах.

Ключевые слова: тонкостенные конструкции, вентиляторная градирня, коррозионный износ, экспериментально-теоретический метод, механические свойства, тонкостенные элементы, дефекты, высокая температура, интерполяционные сплайны, вариант метода конечных элементов, напряженно-деформированное состояние, упругие и пластические деформации

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1. Introduction

The structure of a fan cooling tower (Figure 1, *a, b*) is a complex spatially curved system of reinforced concrete and steel elements. The inclined supports and cylindrical part of the cooling tower are made of reinforced concrete [1]. The metal part consists of a reducer — a converging truncated conical shell, a neck — fragments of toroidal and cylindrical shells, and a diffuser — a diverging truncated conical shell. The 4 mm thick shells are reinforced on the outside with a longitudinal and transverse set of channels, angles and plates. At the neck level and near the upper section of the diffuser, the structure is strengthened with ribs that are fixed to the cooling tower body with bars. The cooling tower design includes technological windows, as well as platforms and a stair system for maintenance.

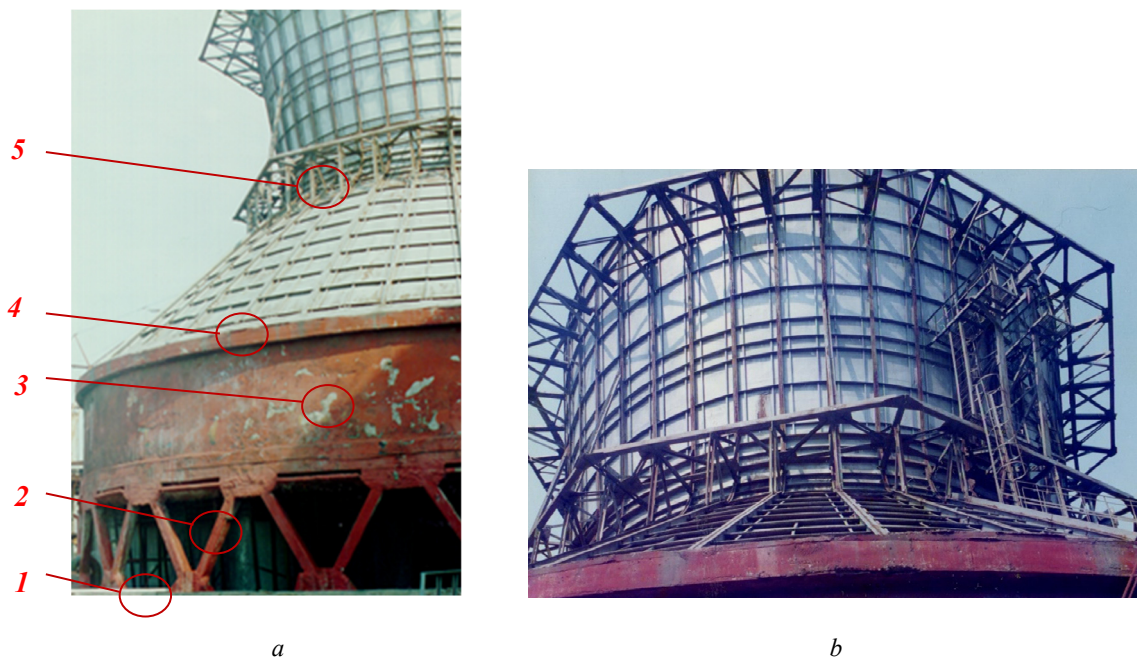


Figure 1. Large-sized cooling tower:
a — general view; *b* — metal part
 Source: compiled by N.M. Yakupov

In addition to wind, vacuum, and weight loads, the cooling tower structure is subjected to vibration loads. Vacuum and vibration loads occur during the operational period when the fan is running. The internal surfaces of the structures are exposed to relatively high temperatures from contact with cooled water (up to 60°C and above), while the external surfaces and part of the internal surface are constantly exposed to the ambient temperature.

Severe service conditions contribute to intense corrosion wear. Field surveys of the condition of the structural elements of a number of cooling towers have shown that reinforced concrete supports and part of the metal shell are most susceptible to corrosion wear.

During more than 20 years of operation, the strength of concrete for some columns has significantly decreased. Concrete loosens, micro and macro cracks develop, and corrosion spots appear in the reinforcement. As a result, the strength properties of reinforced concrete structures are reduced. Figures 2 and 3 show fragments of the most worn areas *1, 2, and 3* (according to Figure 1) of the reinforced concrete structural elements.

In the metal part of the cooling tower, the neck area is experiences maximum corrosion wear, where the maximum air flow velocity, high vibration loads, and the greatest temperature impact take place. As a result of intense corrosion, the thickness of the shell has decreased significantly, in particular, in the neck

area; the thickness has decreased to 2 mm. There are a large number of holes and local depressions. A number of shell panels have turned into a “sieve”. This pattern is observed in the neck area and in the lower parts of the reducer and diffuser. Active corrosion wear occurs at the panel joints, in the narrow gaps between the panel elements, and above the stiffening ribs. The supporting elements of the cooling tower, due to their external location, show less wear. Figure 3 shows some fragments of the most worn structural elements in the area where the reducer rests on the upper reinforced concrete ring (region 4 in Figure 1) and in the neck area (region 5 in Figure 1).

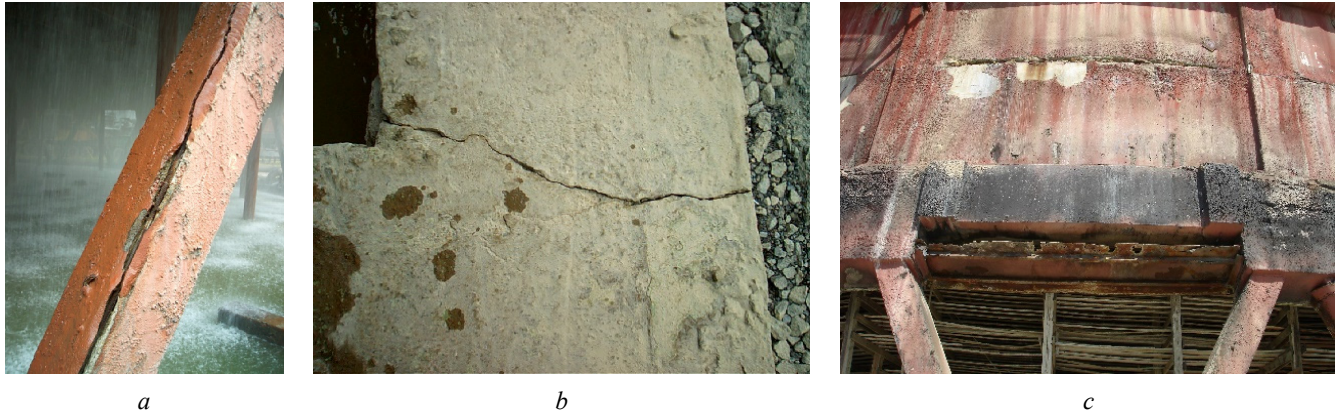


Figure 2. Defects (according to Figure 1):
a — in the area of inclined supports; *b* — in the area of the base; *c* — in the cylindrical part
 Source: compiled by S.N. Yakupov.

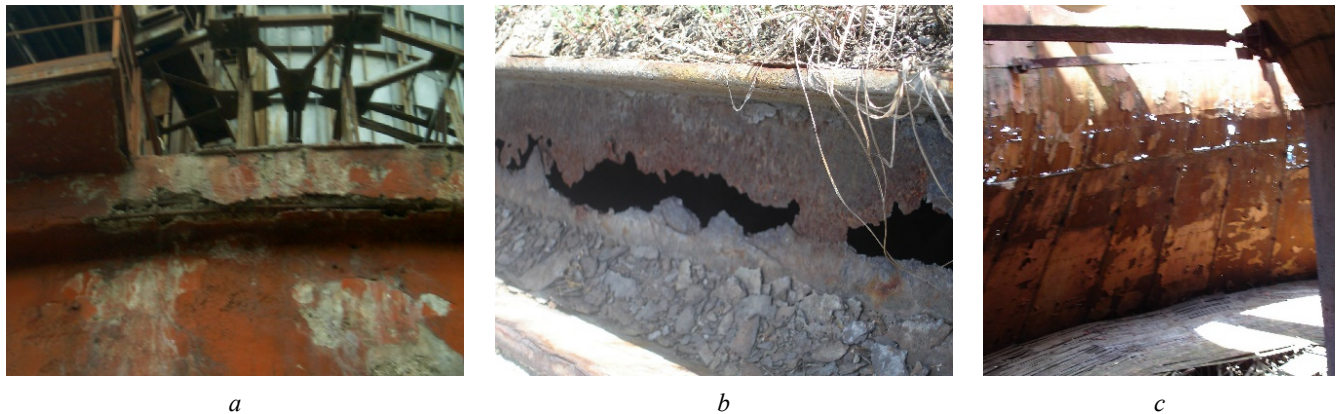


Figure 3. Defects:
a — in the area of the upper reinforced concrete ring; *b* — in the reducer in the area of the reinforced concrete ring; *c* — in the area of the neck (inside view)
 Source: compiled by S.N. Yakupov.

Metal corrosion is a physical and chemical interaction between metal and the environment — the oxidation of metal with the formation of corrosion products (rust), resulting in the reduction of the geometric parameters of structural elements. Upon that, the surface layers of structural elements are loosened to a certain depth or to the entire depth for thin-walled elements, which changes the mechanical properties of the element.

A thin protective passivating layer forms on the metal surface in water or other environments (Figure 4). When this layer is destroyed, corrosion damage begins [2].

It is evident that various factors influence the destruction of the protective passivating layer: physical and mechanical fields, environment and temperature, and others.

The influence of stress state on the kinetics of corrosion processes has been previously considered by the authors. Studies have shown that an increase in tensile stress contributes to the destruction of the protective layer and, thus, leads to accelerated corrosion wear. When analyzing the performance of structures, especially thin-walled structures exposed to corrosion, in addition to changes in geometric parameters, it is necessary to take into account changes in the reduced mechanical properties, as well as the level and nature of mechanical loads.

The influence of various physical fields on the state of the protective passivating layer has not been sufficiently studied. The influence of an active magnetic field on the corrosion process has been noted in [3–10].

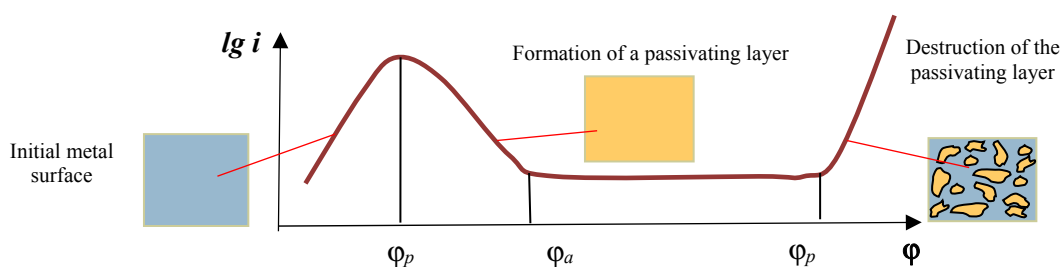


Figure 4. Relationship between the rate of anodic dissolution of metal i and the potential ϕ
 Source: compiled by N.M. Yakupov

In structural design, the amount of material wear per unit of time (e.g., 0.1 mm per year) is generally specified. This approach does not take into account changes in the integral mechanical properties of thin-walled structural elements, as well as the formation of local depressions and holes. The results of a study of thin-walled beams with local defects are given in [13]. Some results of studying the influence of the environment on the creep and long-term strength of metals are given in [14–16]. The influence of vibration on the corrosion rate of protective anodes made of magnesium, aluminum, and zinc in fresh and sea water of the Persian Gulf is noted in [17]. The results of a study of the influence of vibration excitation during high-temperature processing on the mechanical properties and corrosion resistance of cast steel under stress are presented in [18].

The aim of this work is to develop an approach for diagnostics of thin-walled structures exposed to corrosion wear in the presence of vibration and elevated temperatures, using the example of a large-scale fan cooling tower. Research objectives: investigation of the effect of vibration and temperature on the corrosion wear process in thin-walled structural elements using a combined experimental and theoretical method; stress analysis of the initial and current condition of the metal part of the fan cooling tower, taking into account plastic deformations based on a version of the finite element method [11] developed for calculating stress-strain state of structures in cylindrical coordinate system.

2. Method

To evaluate the degree of corrosion wear of samples exposed to vibration and temperature field for a specific period of time in a given environment, a combined experimental-theoretical method [12] is used, based on the synthesis of experimental data and theoretical relationships obtained from nonlinear shell theory. This approach is an effective method for evaluating the integral stiffness properties of various thin-walled elements of complex structures. A diagram of the setup for flat samples is shown in Figure 5.

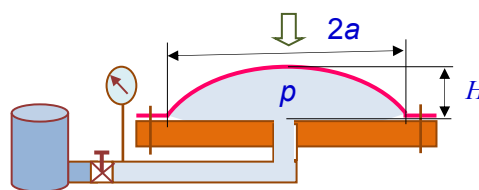


Figure 5. Diagram of the experimental setup
 Source: compiled by N.M. Yakupov.

Round samples, aged for a specific period of time in the test environment under vibration and temperature exposure, are restrained along their contour and loaded with uniform pressure p . As pressure p increases, the shape of the dome is monitored, in particular, rise H of the dome is measured, and a pressure p — deflection H graph is constructed. At the theoretical stage, using the ratios obtained from nonlinear shell theory for the case of moderate bending and the experimental pressure p — deflection H relationship for metal samples, the reduced tangential stiffness for tension-compression B and the reduced bending stiffness D are calculated [12]:

$$B = 0.3037pa \left(\frac{a}{H} \right)^3, \quad D = 0.0253p \frac{a^4 h^2}{H^3}, \quad (1)$$

and also the modulus of elasticity, according to formula:

$$E = \frac{0.303pa^4(1-\nu^2)}{hH^3}, \quad (2)$$

where h and a — the thickness and radius of the test part; ν — the Poisson's ratio.

3. Results

3.1. Influence of Vibration on Corrosion Wear

A study of the influence of vibration on the corrosion wear process of St3 steel samples with an initial thickness $h = 0.6$ mm in an aqueous medium has been conducted.

Thin round samples are placed separately in containers with the medium. The containers are placed on a vibrating platform. Specifically, on a platform attached to a compressor (rotation frequency $n = 2800$ rev / min).

Cases of horizontal and vertical sample placement are considered (Figure 6, *a*, *b*).

The samples were kept in the aqueous medium for a specified period of time. The control group of containers was located in an area free from vibration. The degree of corrosion of the samples was evaluated using a combined experimental-theoretical method [12].

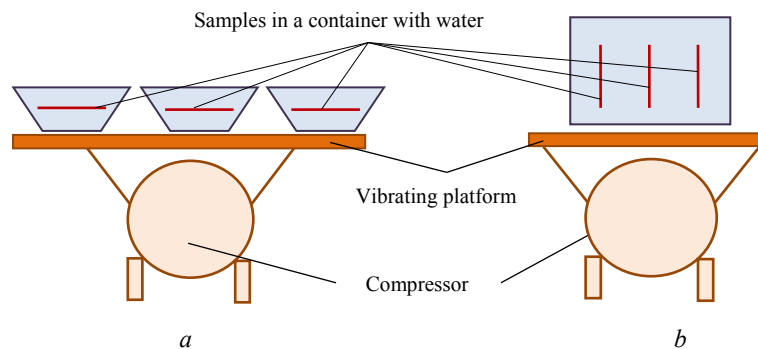


Figure 6. Schemes for placing samples on a vibrating platform:
a — horizontal placement of samples; *b* — vertical placement of samples

Source: compiled by N.M. Yakupov.

In the first series of tests, samples were placed horizontally on a special compressor platform (Figure 6, *a*). The compressor turned on automatically for two months (except Sundays) from 9:00 a.m. to 6:00 p.m.: during the day, the compressor periodically turned on (vibration — 20 seconds) and off (no vibration — 3 minutes 40 seconds).

In the second series of tests, samples were placed vertically on a special compressor platform (Figure 6, *b*). The compressor operated for four months in automatic mode: it turned on (vibration) for 30 seconds and turned off (no vibration) for 6 minutes and 10 seconds. In each series of tests, the control group of samples, that were not subjected to vibration, was examined.

Using the combined experimental-theoretical method mentioned above, the relationship between the maximum deflection H and pressure p was determined for each sample. Pressure p — deflection H curves were constructed based on the average values of the maximum deflections of the samples, which are presented for the first series of tests in Figure 7, *a*, and for the second series — in Figure 7, *b*.

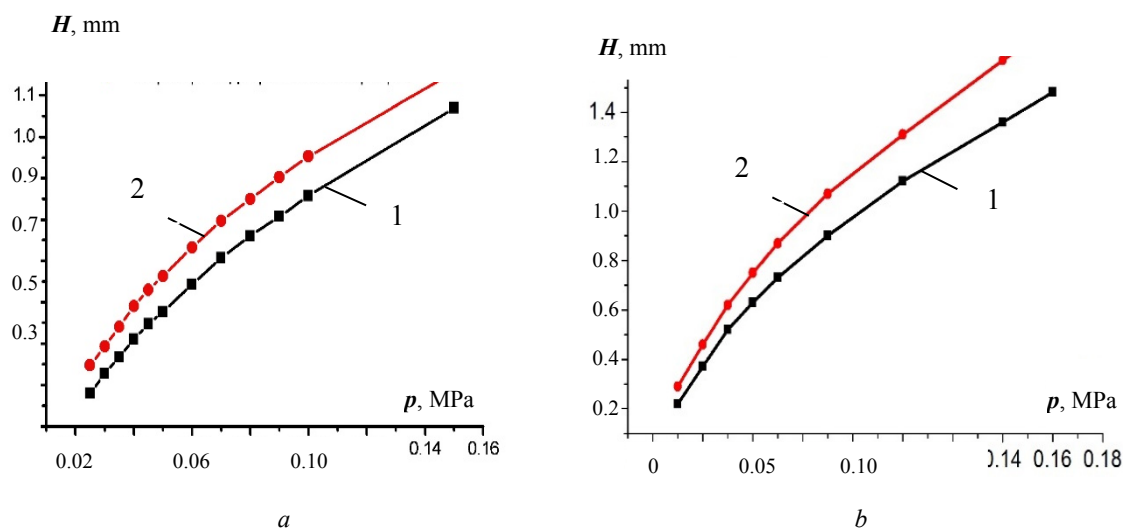


Figure 7. $p - H$ relationships when samples are placed:
a — horizontally, *b* — vertically; 1 — at rest; 2 — under vibration
 Source: compiled by N.M. Yakupov.

As can be seen, in both series of tests, samples from the group exposed to vibration (2) deflect more than samples from the control group (1) at the same pressure, i.e., samples under vibration experience greater corrosion wear than samples from the control group. This conclusion is consistent with the measurements of the thickness of the samples after corrosion wear: the average thickness of the samples exposed to vibration in the first series of tests was 0.588 mm, while the average thickness of the samples in the control group was 0.593 mm. For the second series of tests, the corresponding values were 0.556 mm and 0.569 mm.

This conclusion can be explained by the fact that vibration creates more favorable conditions for the destruction of the passivating layer in the electrochemical corrosion process.

Thus, the influence of vibration on the process of corrosion wear of steel samples in an aqueous medium has been established, with vibration contributing to faster destruction of the protective passivating layer formed during corrosion, thereby promoting accelerated corrosion.

The discovered effect is of high theoretical significance to the study of corrosion as a complex electrochemical process under the influence of vibration, and of practical significance as well. The effect must be taken into account in the design and operation of metal structures that experience substantial vibration loads, such as fan cooling towers, vehicles, pipelines, and others.

3.2. Influence of Temperature on Corrosion Wear

The effect of temperature on the corrosion process is of particular scientific interest, although studies on this topic are rare. An increase in corrosion wear at 70°C was discovered at a coal-fired power plant during a study of boiler walls, where viscous deposits were observed on the walls due to acid condensation

[19]. An increase in susceptibility to stress corrosion cracking for some grades of stainless steel in *KCl* solution under the influence of temperature was noted in [20].

An experimental study of the influence of water temperature on the corrosion wear of thin-walled St3 steel samples has been conducted.

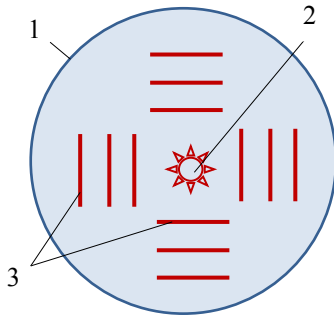


Figure 8. Installation scheme:
1 — cylindrical container; 2 — heating element; 3 — sample holders
Source: compiled by N.M. Yakupov.

Experimental procedure. A setup has been developed (Figure 8) consisting of a cylindrical container (1) for filling with aggressive liquid.

A heating element (2) is located in the center of the container. Sample holders (3) are installed around the perimeter of the container at equal distances from the center. Temperature sensors are installed near the samples to monitor the temperature of the medium.

In the experiment, three installations located next to each other were used to implement three temperature modes. Samples fixed in a holder are placed in appropriate containers with a particular medium and kept there for a particular period of time. Before and after the experiment, the thickness of the samples under study is inspected and measured.

To evaluate the influence of temperature on the corrosion of circular thin-walled specimens, the combined experimental-theoretical method mentioned above is used.

St3 steel samples with a thickness of 0.6 mm were exposed to corrosion wear over 107 days in the following temperature modes: $T_1 = 70^\circ\text{C}$, $T_2 = 40^\circ\text{C}$, $T_3 = 18^\circ\text{C}$. The thicknesses of the samples subjected to corrosion under the influence of the temperature field were as follows: $t_1 = 0.528$ mm, $t_2 = 0.576$ mm, $t_3 = 0.581$ mm, respectively. The “pressure p — deflection H ” curves for the considered samples are presented in Figure 9.

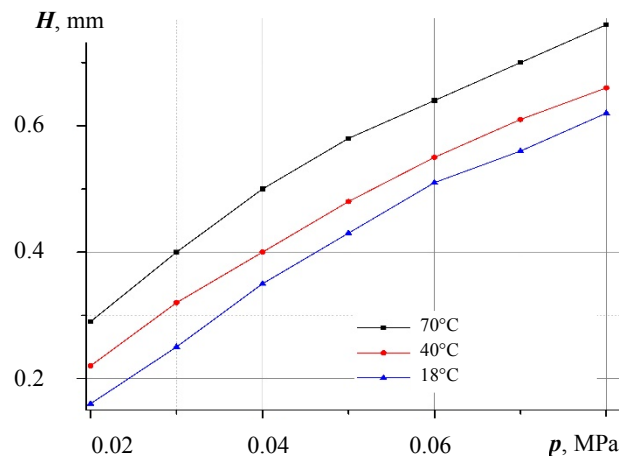


Figure 9. Pressure p — deflection H curves
Source: compiled by R.R. Giniyatullin.

As seen in Figure 9, as the temperature of the medium increases, the deflection of the samples increases, i.e., corrosion wear increases. The resulting elasticity moduli of the corroded samples, calculated according to (2) at $p = 0.02$ MPa, were: $E_1 = 1.778 \times 10^6$ MPa, $E_2 = 1.946 \times 10^6$ MPa, $E_3 = 2.051 \times 10^6$ MPa, respectively.

Figure 10 shows images of the surface of corroded samples at 4x, 10x, and 400x magnification.

As can be seen, corrosion causes the surface of the samples to loosen to a certain depth, and as the temperature rises, cavities form, which merge into large regions at 70°C .

Thus, it has been established that the temperature of the environment significantly affects the corrosion wear of thin-walled steel samples. An increase in the temperature of the environment contributes to a more rapid destruction of the protective passivating layer formed during the corrosion process, thereby leading to an increase in the degree of corrosion wear.

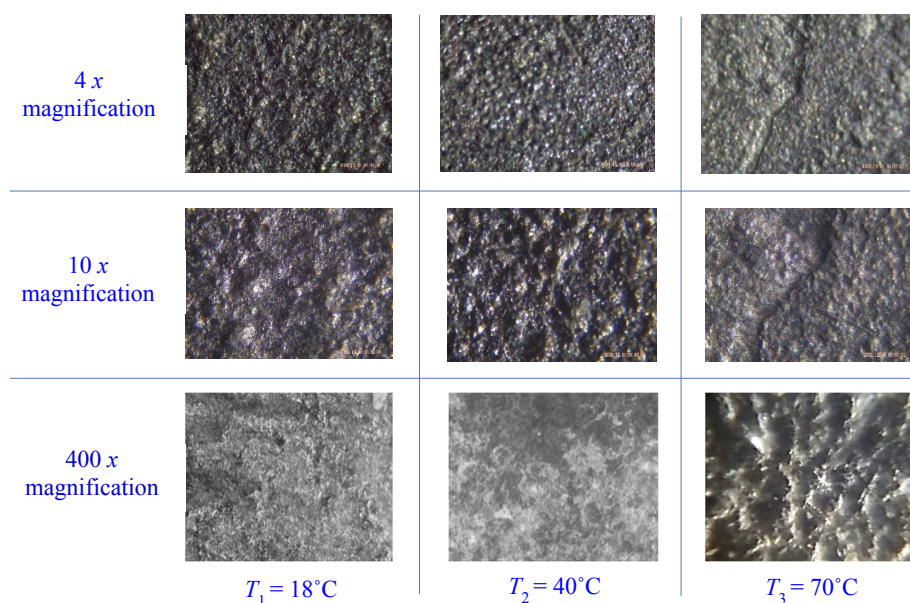


Figure 10. Images of the surface of corroded samples

Source: compiled by R.R. Giniyatullin.

The established effect is of high theoretical significance in studying the complex electrochemical process of corrosion, taking into account the temperature of the environment. The effect is also of high practical significance, especially for thin-walled structural elements, and must be taken into account in the design and operation of metal structures that interact with high-temperature environments during service, such as fan cooling towers, pipelines, and others.

3.3. Structural Condition of Cooling Tower with Corrosion Defects

As noted above, cooling tower structures operate in severe conditions. Wind, vacuum, and weight loads, as well as vibration from operating fans, high temperatures of the cooled medium, and solar radiation contribute to significant corrosion wear of the structural elements. This results in the formation of various local depressions and holes, and changes in the stiffness properties of the thin-walled elements. All this contributes to an increase in internal stress, appearance of additional stress concentrators, and a reduction in the load-bearing capacity of the entire structure.

In the region of the corrosion defect, the structure of the surface layer material changes. This fact is practically ignored, although it can be critical for thin-walled structural elements. Changes in the structure of the surface layer can lead to significant changes in the integral mechanical properties of thin-walled structural elements. In this regard, to perform the stress analysis of the metal part of the cooling tower structure (Figure 1), the current integral stiffness characteristics of thin-walled elements cut out from the structures during repair were preliminarily determined using the combined experimental-theoretical method. That is, the calculations took into account the actual stiffness properties of the structural elements, which were subjected, in particular, to the influence of vibration and temperature loads during the operational period.

To perform the stress analysis of the metal part of the fan cooling tower, a spline version of the finite element method (*SV FEM-2*) [11] was used, developed for the case of plastic deformation. The method was

developed by the authors. The method is based on a synthesis of the idea of preliminary parameterization of the mid-surface of the shell in a cylindrical coordinate system and the finite element method. The method allows one to determine the stress-strain state of thin-walled structures under static loads. The effects of vibration and temperature are taken into account by specifying relevant integral stiffness characteristics for structural elements. The key points of the spline version of the finite element method (SV FEM-2) are presented below.

Parameterization of the middle surface of the cooling tower shell. The parametric equation in the cylindrical coordinate system used in the cooling tower analysis is as follows:

$$r(t^1, t^2) = x(t^1, t^2)i + \rho(t^1, t^2)e(t^1, t^2)e(t^1, t^2) = \sin \psi(t^1, t^2)j + \cos \psi(t^1, t^2)k, \quad (3)$$

where $x(t^1, t^2)$ — the linear coordinates; $\psi(t^1, t^2)$ — the angular coordinates; $\rho(t^1, t^2)$ — the shortest distance from axis OX to the middle surface of the shell; t^1, t^2 — the parameters of the unit square; i, j, k — the unit vectors of orthogonal axes OX, OY, OZ .

By differentiating position vector r , coordinate vectors r_1 and r_2 , the components of the first a_{jk} and second b_{ik} metric tensors and Christoffel symbols Γ_{jk}^i are determined.

Geometrical and physical relationships. The case of moderate bending of a thin shell is considered. In this case, the tangential and bending strains of the mid-surface according to the Kirchhoff — Love model are determined by the formulas [20]

$$2\varepsilon_{ik} = e_{ik} + e_{ki} + \omega_i \omega_k, \quad \kappa_{ik} = -\nabla_i \omega_k - b_i^s e_{ks}, \quad (4)$$

where $i, k, s = 1, 2$; ε_{ik} are the covariant components of the tangential strain tensor; κ_{ik} are the covariant components of the bending and torsional strains; $\omega_i = \nabla_i w + b_i^k u_k$ are the components of the normal line rotation vector m ; $e_{ik} = \nabla_i u_k - b_{ik} w$ are the components of the rotation tensor; ∇_i is the symbol of covariant differentiation with respect to a_{ik} ; u_k, w are the covariant components of the displacement vector ($u_1 = u, u_2 = v$), b_i^s are the mixed components of the second metric tensor.

The relationship between stress intensity σ_i and strain intensity ε_i is taken in the form

$$\sigma_i = g(\varepsilon_i)\varepsilon_i. \quad (5)$$

Here $g(\varepsilon_i)$ is a positive function, characteristic for the considered material.

Resolving equations. To derive the resolving equations, Lagrange variational equation is used [11]

$$\delta W - \delta A = 0, \quad (6)$$

where δW — the variation of the strain potential energy of the shell, δA — the work of the external forces applied to the shell.

In each rectangle Ω_j of the unit square area the solution is expressed in the form of interpolational Hermite cubic spline of two variables

$$u = \varphi(s^1)F_u\varphi(s^2), \quad v = \varphi(s^1)F_v\varphi(s^2), \quad w = \varphi(s^1)F_w\varphi(s^2), \quad (7)$$

where $\varphi(s^1), \varphi(s^2)$ — the vectors of coordinate functions; F_u, F_v, F_w — the matrices of nodal values of the displacement components, the first and the second mixed derivatives.

The use of preliminary parameterization and the representation of the solution in each rectangle Ω_j in the form of a cubic spline ensure geometric continuity, as well as the continuity of the displacement function

and its first derivatives throughout the entire considered domain Ω , which is an important condition for convergence to the exact solution as the size of rectangles Ω_j decreases. Thus, it is possible to obtain consistent elements based on the Kirchhoff — Love hypothesis for shells of complex geometry.

By substituting variations of displacements and strains into the Lagrange variational equations and taking into account the independence of nodal displacements and their derivatives, after a series of transformations, a system of algebraic equations is obtained

$$[A]\{U\} = \{R\}_p + \{R\}_n. \tag{8}$$

Here $[A]$ is the symmetric stiffness matrix of the system of band structure, $\{U\}$ is the vector of unknowns, $\{R\}_p$ is the load vector, $\{R\}_n$ is the vector of nonlinear components. The solution to the resulting system of nonlinear algebraic equations is determined using the general iteration method.

The algorithm of the above-mentioned spline version of the finite element method for calculating the stress-strain state of shell structures of complex geometry in a cylindrical coordinate system is implemented by the SV FEM-2 software package.

Stress analysis of the metal part of a fan cooling tower, taking into account physical nonlinearity. Based on the spline version of the finite element method (SV FEM-2) [11], developed to calculate the stresses and strains of shell structures with complex geometry in a cylindrical coordinate system, taking into account physical nonlinearity, the stress analysis of the metal part of a fan cooling tower is performed (Figure 11).

Information about the ribs is specified at each calculation point in the following format: area, static moment, and moment of inertia of the rib section. Due to the presence of a plane of symmetry, half of the structure is considered, which is divided into 10 elements along the circumferential coordinate (angle θ°) and 23 — along the generatrix. The horizontal sections (Figure 11) are numbered from bottom to top. The zero angle corresponds to the wind direction plane. The distribution of pressure from wind load, both along the height and the circumferential coordinate, is taken in accordance with the building code in force in the Russian Federation, SP 20.13330.2016¹.

The current mechanical characteristics of the thin-walled structural elements were determined using the combined experimental-theoretical method described above. Samples were cut from a cooling tower structure that had been shut down for major repairs. Changes in shell thickness t along the generatrix and the degree of wear of horizontal ribs W for the current version (for some of the most worn sections according to Figure 11) are shown in the Table.

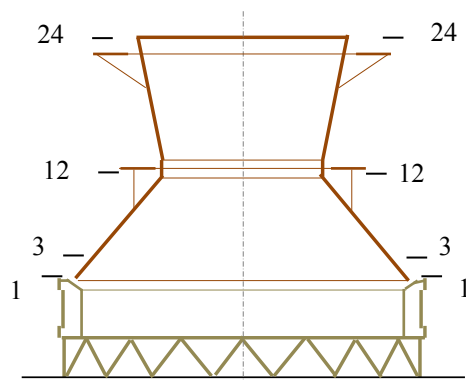


Figure 11. Design diagram of a fan cooling tower
Source: compiled by N.M. Yakupov.

Change in shell thickness and degree of wear of horizontal ribs

Section	1–1	2–2	3–3	4–4	8–8	9–9	10–10	11–11	12–12	13–13	14–14
t, mm	0,35	0,30	0,10	0,00	0,05	0,30	0,35	0,30	0,10	0,05	0,10
$W, \%$	40	30	10	0	5	30	40	30	10	5	10

Source: compiled by N.M. Yakupov.

¹ SP 20.13330.2016. Set of rules “Loads and actions”. JSC “Research center “Construction” — V.A. Kucherenko Central Scientific Research Institute for Building Structures, 2017.

The displacement and stress distributions for the initial and current cooling tower designs were analyzed. Significant stress concentrations were identified in defective areas of the structures, formed as a result of corrosion wear under the influence of vibration from operating fans, high temperatures from the cooled medium, solar radiation, as well as wind, vacuum, and weight loads. The maximum values of stress intensity σ_i along circumferential coordinate θ° at maximum load in a linear setting for the first two horizontal calculated sections (according to Figure 11) are shown in Figure 12 (section 1–1) and Figure 13 (section 2–2).

As seen in Figure 12, stress concentrations in the first section (the area where the reducer is supported by the reinforced concrete part of the cooling tower) are observed in the region of $\theta = 36^\circ$ and $\theta = 160^\circ$. In the second section (Figure 13), a stress peak is observed in the zone of $\theta = 63^\circ$. For the current version, the linear stress exceeds the yield strength for this material ($\sigma_m = 200$ MPa).

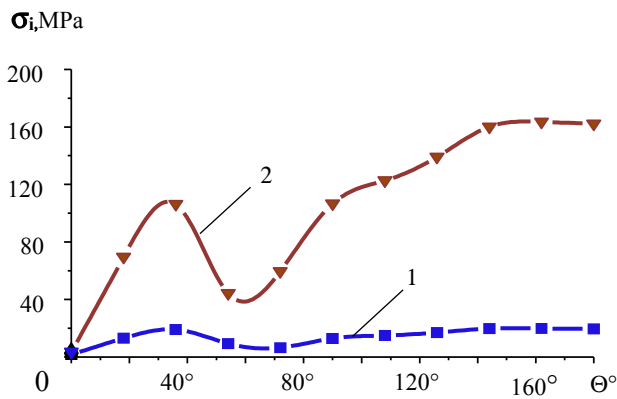


Figure 12. σ_i - θ° relationship for section 1–1:
1 — initial; 2 — actual
Source: compiled by N.M. Yakupov.

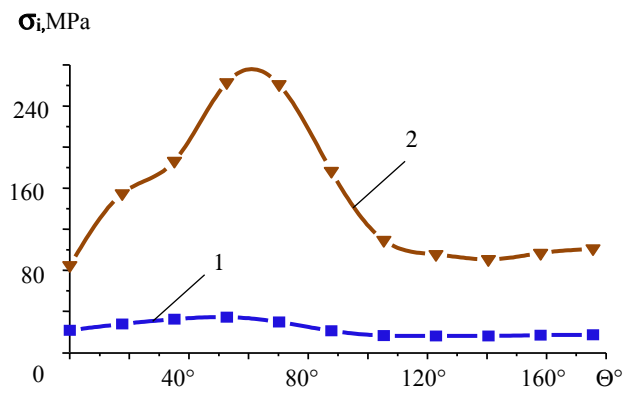


Figure 13. σ_i - θ° relationship for section 2–2:
1 — initial; 2 — actual
Source: compiled by N.M. Yakupov.

Figure 14 shows the changes in stress intensity depending on the load value for points *D* and *C* located in section 1–1; point *D* is at some distance from point *C*, where maximum stresses occur.

Line *F* corresponds to $\sigma_m = 200$ MPa. As seen from Figure 14 at 82% of the maximum load at point *C*, the stress reaches σ_m and effectively does not increase further.

At point *D*, starting at 82% load, as expected, a more intense increase in stress is observed. That is, load redistribution occurs.

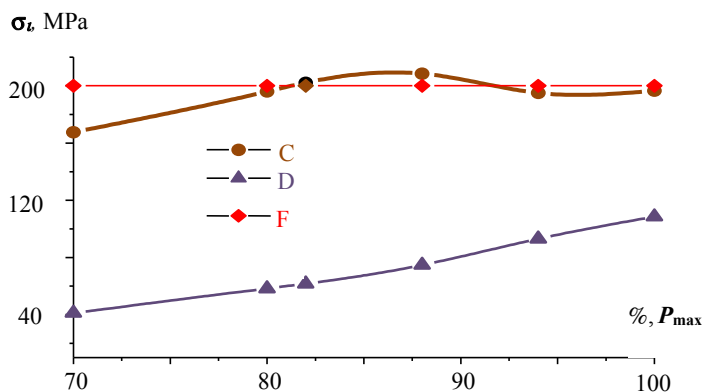


Figure 14. Dependence σ_i -*P* for points *D* and *C* located in section 1–1
Source: compiled by N.M. Yakupov.

Thus, a spline version of the finite element method in a cylindrical coordinate system has been developed, taking into account plastic deformations. Stress analysis for the initial and current condition of the metal part of the fan cooling tower has been performed. The current mechanical properties of thin-walled structural elements were determined using a combined experimental-theoretical method. In particular, it was established that corrosion wear leads to a significant increase in stress, which may exceed the yield strength of the material. At the same time, the resulting plastic deformations lead to a redistribution of stresses.

4. Conclusion

According to the results of the conducted research, the following should be noted:

1. An approach for diagnostics of metal structures is described using the example of a large-scale fan cooling tower, which is exposed to the combined effects of vibration and elevated temperatures.

2. The corrosion wear of thin-walled steel structural elements exposed to vibration and temperature was investigated using a combined experimental-theoretical method.

3. It has been established that vibration and elevated ambient temperatures contribute to the accelerated destruction of the protective passivating layer of the thin-walled steel elements and thus contribute to accelerated corrosion. At the same time, the effect intensifies with increasing temperature and duration of exposure to vibration.

4. A spline version of the finite element method was developed in a cylindrical coordinate system, and stress analysis was performed for the metal part of the fan cooling tower, taking into account plastic deformations for the initial and current condition of the metal part. When analyzing the current condition, corrosion defects and changes in the stiffness properties of the thin-walled elements caused during operation as a result of the combined effects of vibration and high temperatures were taken into account.

5. It has been established that corrosion wear leads to a significant stress increase in the structural elements, which may exceed the yield strength of the material, while the resulting plastic deformations lead to stress redistribution.

The obtained results are of high theoretical and practical importance and need to be taken into account in the design and operation of metal structures that are exposed to significant vibration loads and operate at high temperatures and under the influence of various types of radiation.

To address the issue of safe operation of thin-walled structures exposed to corrosion wear, when diagnosing their condition, in addition to considering changes in the geometric parameters, it is necessary to consider changes in the mechanical characteristics due to the influence of external factors, in particular vibration, ambient temperature, and physical fields.

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