ISSN 2413-6212 (Online), ISSN 2227-1252 (Print)
Мости та тунелі: теорія, дослідження, практика, 2025, № 27

МОСТИ ТА ТУНЕЛІ: ТЕОРІЯ, ДОСЛІДЖЕННЯ, ПРАКТИКА

УДК 519.87:624.014-027.45

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ASSESSMENT OF THE IMPACT OF OPERATING CONDITIONS ON THE RELIABILITY OF BAR-TYPE STEEL STRUCTURES

Purpose. The study aims to develop a comprehensive approach to calculating the residual service life of spatial multi-element steel bar structures, taking into account both predictable and random factors that affect the structures or their individual elements throughout their service life. **Methodology.** The key causes of corrosion damage are examined, and models of corrosion wear are analyzed, including those that consider the effects of mechanical stresses and aggressive environments. The use of different types of survivability indicators – both deterministic and stochastic – allows for a more accurate assessment of structural reliability under real operating conditions. It is noted that current construction standards insufficiently account for the time-dependent development of defects, which complicates the assessment of the residual service life of structures. The need for a comprehensive approach to forecasting the reliability and durability of steel structures in actual service conditions is emphasized. **Findings.** It is demonstrated that traditional calculation methods do not adequately assess the durability and survivability of structures with evolving defects. An approach to evaluating the survivability of steel structures is proposed, based on the use of both deterministic and stochastic indicators. This allows for consideration of both systematic and random changes in the behavior of the structural system. The advantage of mathematical modeling over physical modeling is substantiated, particularly in its ability to account for multiple scenarios of corrosion development and the complex interaction of corrosion with mechanical influences. Parameters characterizing the condition of a structure under corrosion wear have been identified. **Originality.** A comprehensive approach to assessing the reliability and survivability of bar-type steel structures under corrosion wear has been developed, based on a combination of deterministic and stochastic indicators. Mathematical models of corrosion damage are considered, taking into account the influence of both stress–strain state and aggressive environments. **Practical value.** The obtained results can be used in the design, diagnostics, and forecasting of the technical condition of bar-type steel structures operating in aggressive environments and exposed to various types of loads.

Keywords: operational reliability; survivability; steel bar structures; corrosion wear; mathematical models

Introduction

In recent years, the problem of reduced durability of building structures during operation has become one of the priority issues in both scientific research and construction practice. A significant number of construction facilities require unscheduled repairs, and some fail before reaching their designated service life. The service life of buildings and structures is determined by the duration of the functional state of the main load-bearing elements, whose physical deterioration is accelerated by the influence of individual factors or their combinations.

The implementation of advanced technological processes and the production of new materials often involve the use of various aggressive working environments, which lead to the premature destruction of structural elements and equipment. Conditions where aggressive media and mechanical loads act simultaneously are typical for many industries, including chemical, mining, oil and gas, metallurgy, construction, and others. Therefore, the task of developing effective structural solutions for such operational conditions remains highly relevant (Zyma, Steblianko, Pahomov, & Mytrofanov, 2023; Макаренко, Бондаренко, Винников, & al., 2024; Макаренко, Винников, Гоц, & al., 2025; Ниркова, 2023).

The reduction in the load-bearing capacity of structural elements can occur at any stage of the life cycle prior to failure under ultimate limit states during operation. Given the high requirements for economic efficiency, reliability, and durability of structures, as well as the need to minimize material consumption, the design of such facilities must be carried out with the assumption that key structural parameters should be defined at the design stage, with mandatory consideration of the specific operating conditions. Thus, comprehensive work is required at the design stage, including the selection of optimal design solutions, materials and accurate calculations that take into account all possible impacts during operation (Alshoaibi, Ghazwani, & Hakami, 2021; Keshmiry, Hassani, Mousavi, & Dackermann, 2023; Llanes-Tizoc, Reyes-Salazar, Ruiz, Valenzuela-Beltrán, Bojorquez, & Chávez, 2020).

Purpose

The purpose of this work is to analyze the operational features of steel bar structures under aggressive environmental conditions and variable loads, to identify the main causes and mechanisms of corrosion damage, and to justify the necessity of accounting for the potential development of defects at the design stage to improve the reliability and durability of structures.

The object of the study is multi-element steel bar structures subjected to corrosion wear and operational damage.

The subject of the study is the processes of corrosion destruction and the patterns of changes in the strength characteristics of steel structural elements, the analysis of corrosion models, as well as methods for improving structural survivability and assessing residual service life, taking into account material defects and operating conditions.

To achieve the stated objective, the following research methods are employed: analysis of regulatory and scientific literature; methods of structural mechanics; mathematical modeling of corrosion destruction and deformation processes of structural elements under changing operating conditions; and methods for assessing the residual service life of structures under complex external influences.

Methodology

Bar-type steel structures occupy a special place among construction systems. They are widely used in various industrial sectors (trestles, galleries, towers, masts, bridges). These structures are subjected to quasi-static, cyclic, dynamic, and random loads. They operate under corrosive environmental conditions and are exposed to temperature fluctuations (Ivanova, Solodyankin, Yanko, & Barsukova, 2022). The building codes and standards used in the design of structures do not account for the calculation of systems with developing defects and do not allow for predicting the behavior of a structure in emergency situations (ДСТУ-Н Б В.2.6-186:2013, 2013; ДБН В.2.6-198:2014, 2014). The problem of determining the durability of a structure or its elements exposed to aggressive operating environments and loads is directly related to their reliable and accident-free operation.

Reliability is the property of a system to perform its functions in a specified mode for a specified period with a given probability. The concept of reliability is closely linked to the concept of survivability (Ivanova, Hapieiev, Shapoval, et al., 2021).

It is important to distinguish between general indicators of survivability, which are universal for all types of load-bearing structures, and specific indicators, which vary depending on the structural form. These characteristics arise from considering the structure as an integrated whole – a system of interacting elements. In this context, it becomes evident that the system's structure is one of the most critical factors in shaping its survivability, and it cannot be reduced merely to the sum of characteristics of individual elements (Ivanova, Zhabchyk, Khoziaikina, & Hryhoriev, 2023).

However, even with an optimal system structure, its reliability can be significantly reduced due to vulnerability to external destructive influences. One of the most common factors weakening the stability of a structural system as a whole is corrosion.

The causes of metal corrosion are diverse, but the key reason lies in the thermodynamic instability of most metals and alloys (with the exception of noble and highly alloyed ones) when exposed to

ISSN 2413-6212 (Online), ISSN 2227-1252 (Print)
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atmospheric or other corrosive environments. Iron and low-alloy steels are also susceptible to corrosion, as the surface oxide film formed during such reactions is insufficiently dense and fails to protect the underlying layers.

The rate and characteristics of corrosion depend on both the composition of the material itself and the nature of the environment, as well as the kinetics of the process. The use of different types of survivability indicators – deterministic and stochastic – allows for a more accurate assessment of structural reliability under specific operating conditions. Deterministic indicators, such as the relationships between destructive parameters and service life, enable the modeling of processes that are subject to precise prediction, whereas stochastic indicators account for random fluctuations and variations in system behavior. These types of indicators are particularly relevant in corrosion wear models, as corrosion processes do not always follow strictly defined patterns. Mathematical models of corrosion that incorporate both deterministic parameters – such as chemical composition and aggressive environmental factors – and random external variations make it possible to more accurately predict the behavior of a structure under various conditions and at different stages of its service life.

Findings

Corrosion is a serious problem and the main damage it causes is not limited to the loss of a certain amount of metal but also includes the failure of entire metal structures or their components, since corrosion leads to a loss of operational reliability. The survivability indicators can be presented as shown in Table 1.

Table 1

Survivability indicators

Formulation	Methodological base
Deterministic	
Static	
Dependence of the selected fracture parameter, for example, the stress intensity factor K_I, on the crack length l: $K_I = f(l)$	Fracture mechanics, finite element modeling
Transfer functions of survivability $w_1 = A/\sigma_{max}$, $w_2 = A/l$, $w_3 = \sigma_{max}/l$, where σ_{max} – maximum stress intensity values; A – area of the structural zone in the state of yield	Theory of control of technical systems, finite element modeling
Dynamic	
The number of loading cycles before failure in the presence of a defect of a given size $N = f(l)$	Fracture mechanics, finite element modeling
Survivability functions $A = f(t)$, $\sigma_{max} = f(l)$	Finite element modeling
Stochastic	
Static	
Probability of failure-free operation with given statistical parameters of highways and the presence of a defect of a given size	Statistical dynamics, fracture mechanics
Dynamic	
Distribution of time of the number of loading cycles before destruction for given statistical parameters and the presence of a defect of a given size	Statistical dynamics, fracture mechanics

Two approaches are used to model corrosion processes: physical and mathematical modeling.

The first approach involves replacing the study of a full-scale object or the technological process it facilitates with experiments on a model that replicates the same physical phenomena under controlled conditions. In other words, it involves reproducing the process that occurs in a structure during operation on test specimens under conditions that ensure the same physical nature of the phenomena. This approach is applied to studying structural elements over an extended period, either under natural conditions or under artificially created environments.

In the second case, the structural element (or the entire structure) is exposed to a more aggressive environment than it would experience in reality, which accelerates the corrosion process. Such experiments yield reliable data on corrosion degradation.

The disadvantages of physical modeling include the lack of reliable methods for transferring results from the physical model to the real structure, as well as the high cost and specificity of each test setup. When transitioning to structures made of metals with different chemical compositions or changing the composition or parameters of the aggressive environment, the obtained models may become invalid. Additionally, laboratory conditions often fail to account for the actual stress-strain state and other influential factors affecting corrosion.

The essence of mathematical modeling lies in selecting an appropriate model that describes the physical process and computing the necessary functional characteristics. The capabilities of mathematical modeling are significantly broader than those of physical modeling, especially for corrosion processes, which are multistage in nature. These stages can occur either sequentially or parallel under various external and internal factors.

A mathematical model can effectively predict the process behavior if it accurately represents the real phenomena. This requires a comprehensive mathematical description of the studied process.

A mathematical model of corrosion is a set of equations that relate corrosion process characteristics to various influencing factors. These include the chemical and phase composition of the metal or alloy, the surface condition of the metal, the operating regime of the metal structure, the characteristics of the corrosive environment, and external influences. Typically, the corrosion process is modeled as a sequential change in the structural state over a specified time interval. Sometimes, the mathematical model is expressed as an explicit function of the structural parameters, initial conditions, time, and environmental factors. However, in most cases, it takes the form of a system of algebraic, differential, or integral equations that connect the progression of the process to external conditions.

The key characteristics of the corrosion process are primarily determined by the chemical composition of the aggressive environment and the material, the microstructure of the surface, temperature, and the stress-strain state of the structure.

Calculation of structures exposed to chemically active aggressive environments comes down to the construction of a calculation scheme and its subsequent analysis. In general, the calculation scheme includes the following models:

Models of a structural element include a schematization of its geometric dimensions and the use of any deformation hypotheses. As a result, a rod, plate, shell, thin-walled or massive structure are used as a model of a structural element.

Material models characterize the properties of the material: brittle, elastic, plastic, creeping.

Load models represent the action of external forces on a structural element.

Models of the impact of an aggressive environment are equations that relate the parameters of the elements of a structure (geometric or mechanical), the parameters of the aggressive environment, time, and the parameters of the stress-strain state of the structure. Unlike problems in the classical formulation, many constants characterizing the properties of an element in a neutral environment become functions. In this case, the degree of their change is usually not the same for different points of the structure. Thus, the impact of an aggressive environment leads to the emergence of induced (time-varying) heterogeneity of geometric and, in some cases, mechanical properties over the area of the structure. The model of an aggressive environment must specify the law of change of induced heterogeneity, in other words, the degree of change of the initial geometric characteristics.

Destructive models are equations or conditions that establish a relationship between the performance parameters of an element or structure at the moment of failure with the parameters that ensure strength. This implies the beginning of the transition from the state of strength to the beginning of destruction.

Reference data on the effect of aggressive environments on metals are either raw experimental material or average values of corrosion parameters. Until recently, in construction regulations, the problem of taking into account the effect of an aggressive environment was generally separated from the problem of calculating structures. It is proposed to take into account corrosion wear by increasing the thickness of a structural element by a value equal to the product of the average corrosion rate and the expected service life of the structure. The given values of the safety factors adopted in calculating the strength and stability of structures require clarification.

The following parameters can be adopted as parameters characterizing the corrosion process:

- depth of corrosion damage *δ;*
- loss of material mass *M*;
- change in cross-sectional area *F;*
- change in strength characteristic *R*.

Obviously, the first three parameters are interconnected and can be expressed one through the other.

The models given do not take into account the influence of the stress-strain state on the rate of the corrosion process. However, in many cases this influence is significant and must be taken into account.

Examples of mathematical models describing the damage process during corrosion wear in some aggressive environments and mathematical models taking into account the influence of mechanical damage are presented in Table 2 (Ivanova, Hapieiev, Shapoval, et al., 2021).

Table 2

Mathematical models of the corrosion process

№	Mathematical models of corrosion damage in aggressive environments	Mathematical models of the corrosion process taking into account the influence of mechanical damage (stress-strain state)
1	$\delta = k\lg_0(\alpha + t_{eq})$	$\frac{d\delta}{dt} = \nu_0(1 + k\sigma)$ ν_0 – stress-free corrosion rate; *K* – coefficient taking into account the stress effect.
2	$\delta = k\left[1 - \exp(\alpha t)\right]$	$\frac{d\delta}{dt} = \nu_0\psi(t) \times (1 + k\sigma)$ $\psi(t)$ – a function of time that takes into account the possibility of slowing down the process due to the formation of oxide films or other products on the metal surface.
3	$\delta = \frac{bt}{t + R}$	$\frac{d\delta}{dt} = \nu_0 exp\frac{V\sigma}{RT}$ *V* – molar volume of metal; *T* – temperature.
4	$\frac{d\delta}{dt} = \alpha\exp(-\beta t)$	$\frac{d\delta}{dt} = \nu_0(1 + k\varepsilon) exp\frac{V\sigma}{RT}$
5	$\frac{d\delta}{dt} = k\delta$	$\frac{d\delta}{dt} = \nu_0 + \alpha\varepsilon(\sigma - \sigma^*)$ α – constant, σ^* – the voltage value at which its magnitude begins to influence the rate of the corrosion process.
6	$\frac{d\delta}{dt} = k\delta(b - \delta)$	$\frac{d\delta}{dt} = \nu_0(1 + kЭ)$ *Э* – specific energy of temperature.

In these models, the depth of corrosion damage is taken as a parameter describing corrosive wear.

Metals and their alloys are the most common structural materials that have found practical application in all areas of industry. Damage to metal structures occurs in a corrosive environment, which can be in the atmosphere, in water, in soils, in technological and working environments of various industries. Damage to metal can occur in different ways: the metal dissolves completely or partially; local destruction (cracks, pitting) occurs in it; some of its mechanical properties change. According to the mechanism of the relationship of the external environment with metals and alloys, corrosion is divided into chemical and electrochemical. The most common is general (solid) corrosion, which involves a fairly uniform dissolution or loosening of the metal surface in an aggressive environment.

The task of calculating structures exposed to aggressive environments comes down to constructing a set of equations describing the deformation

ISSN 2413-6212 (Online), ISSN 2227-1252 (Print)
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and destruction of the structure, diffusion equations, corrosion destruction or other chemical interactions, identifying these equations (determining the values of the coefficients of the equations based on the results of experimental studies), solving the resulting set of equations and analyzing the results obtained.

The question of the influence of corrosion processes on the change in the strength characteristics of metals, primarily the design resistance, has not yet received a definitive answer. When both factors – corrosion and mechanical damage to elements – affect the operation of a structure, which is typical for most metal structures, then such a combination has a significant effect on the strength characteristics of the structure and its elements. Ignoring them can lead to the destruction of both individual elements and the structure as a whole.

Originality and practical value

Consists of a comprehensive approach to assessing the reliability and survivability of rod metal structures operated in aggressive environments and variable loads. The paper substantiates the need to take into account developing damage when designing and assessing the residual life of structures, considers survivability indicators – deterministic and stochastic, as well as mathematical models of corrosion wear. The models considered take into account the influence of the stress-strain state on the rate of corrosion processes, which expands the understanding of the mechanisms of destruction of metal structures and allows to increase the accuracy of predicting their behavior in real operating conditions.

The obtained results can be used in designing, diagnosing and forecasting the technical condition of rod metal structures used in aggressive environments and exposed to various types of loads. Integration of survivability indicators into engineering calculations will provide a more accurate assessment of the safety and stability of objects, especially in conditions of uncertainty and unstable operational factors.

Conclusions

The main causes and mechanisms of corrosion destruction are analyzed, the necessity of taking into account developing damages at the design stage is substantiated. It is shown that reliable operation of rod metal structures in aggressive environments is impossible without taking into account corrosion wear and its influence on the stress-strain state of the structure.

The properties of structures in a damaged state have not been studied sufficiently, as a result of which there is a high risk of their unpredictable behavior, leading to a disruption in operability, including severe accidents and man-made disasters. This is confirmed by the facts of damage and destruction of rod-type structures designed in accordance with current regulatory requirements and classical engineering calculation methods. Traditionally performed calculations for strength, rigidity, stability, and endurance do not completely exclude the possibility of destruction of rod structures. This is due to both the possible presence of damage of various natures and origins in structures, and the excess of the design values by the current loads.

Prospects for further research include improving mathematical models taking into account new data on the material, aggressive environments and operating conditions, which will improve the accuracy of forecasts and adapt designs to more complex and changing operating conditions.

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ОЦІНКА ВПЛИВУ УМОВ ЕКСПЛУАТАЦІЇ НА НАДІЙНІСТЬ РОБОТИ СТЕРЖНЕВИХ МЕТАЛОКОНСТРУКЦІЙ

Мета. Дослідження спрямовано формування комплексного підходу до розрахунку залишкового ресурсу просторових металевих багатоелементних стрижневих конструкцій з урахуванням як прогнозованих, так і випадкових факторів, що впливають на конструкції або їх елементи протягом всього терміну експлуатації. **Методика.** Розглянуто ключові причини корозійного руйнування. Проаналізовано моделі корозійного зносу, що враховують вплив механічних напружень та агресивних середовищ. Використання різних типів показників живучості – детермінованих і стохастичних – дозволяє більш точно оцінювати надійність конструкції з урахуванням умов її експлуатації. Відзначено, що діючі будівельні норми недостатньо враховують розвиток дефектів у часі, що ускладнює оцінку залишкового ресурсу конструкцій. Підкреслено необхідність комплексного підходу до прогнозування надійності та довговічності металоконструкцій у реальних умовах експлуатації. **Результати.** Показано, що традиційні методи розрахунку не дозволяють адекватно оцінити довговічність і живучість конструкцій з дефектами, що розвиваються. Запропоновано підхід до оцінки живучості металоконструкцій, заснований на використанні як детермінованих, так і стохастичних показників, що дозволяє враховувати як закономірні, так і випадкові зміни в поведінці конструктивної системи. Обґрунтовано перевагу математичного моделювання в порівнянні з фізичним, зокрема, у можливості обліку багатоваріантних сценаріїв розвитку корозійних процесів та їх комплексної взаємодії з механічними впливами. Встановлено параметри, що характеризують стан конструкції при корозійному зносі. **Наукова новизна.** Розроблено комплексний підхід до оцінки надійності та живучості стрижневих металоконструкцій з урахуванням корозійного зношування, заснований на поєднанні детермінованих та стохастичних показників, розглянуто математичні моделі корозійної руйнації, які враховують як вплив напружено-деформованого стану так і агресивного середовища. **Практична значимість.** Отримані результати можуть бути використані при проектуванні, діагностиці та прогнозуванні технічного стану стрижневих металоконструкцій, що експлуатуються в агресивних середовищах і піддаються впливу різного виду навантажень.

Ключові слова: експлуатаційна надійність; живучість; металеві стрижневі конструкції; корозійний знос; математичні моделі

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Надійшла до редколегії 04.04.2025.
Прийнята до друку 08.05.2025.