

RESIDUAL SERVICE LIFE ASSESSMENT OF OVERHEAD CRANES UNDER THE COMBINED EFFECTS OF CORROSION, CRACKS, AND DEFORMATION

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ABSTRACT

This paper proposes a methodology for assessing the residual life of overhead cranes based on an integrated diagnostic approach that accounts for the combined effects of corrosion wear, fatigue crack propagation, and deformation of load-bearing elements. A system of coupled differential equations is formulated to describe the time-dependent evolution of damage. In this system, each variable represents a separate degradation mechanism, while the mutual interaction between the mechanisms is taken into account through coupling parameters. The study presents the integration of corrosion, crack, and deformation parameters into a unified methodology for predicting the residual life of overhead cranes. The effects of corrosion, crack development, and deflection in the bridge crane girder are investigated in the form of dimensionless parameters. The use of these parameters makes it possible to quantitatively compare the contribution of each degradation mechanism, identify the limiting factor, and predict residual life without direct dependence on absolute dimensions. This simplifies the analysis and facilitates the justification of measures aimed at extending service life. Numerical examples performed for double-girder overhead cranes show that, under moderate loading and low corrosion activity, the principal factor limiting residual life is fatigue crack propagation. Under severe operating conditions and in highly aggressive corrosive environments, a combined failure mechanism is formed. The proposed methodology can be applied to technical diagnostics, industrial safety assessment, and the development of measures for extending the service life of overhead cranes.

Keywords: diagnostics; residual life; overhead bridge crane; degradation; corrosion; crack; deformation; deflection; integrated approach; fatigue.

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1. Introduction

The SOCAR Oil and Gas Construction Trust is an industrial construction organization with more than 70 years of history and has played an important role in the development of Azerbaijan's oil and gas industry. The Trust is one of the main structural divisions engaged in the construction, installation, repair, and laying of engineering utility networks for offshore and onshore oil and gas infrastructure. With a broad scope of activity ranging from the construction of offshore platforms to the implementation of international projects, the Trust applies modern technologies and implements projects both domestically and internationally. In offshore and onshore construction and installation operations, the Oil and Gas Construction Trust uses hoisting equipment manufactured in various developed countries.

At present, a certain part of the hoisting equipment has exceeded its normative service life. Since hoisting machinery is often designed with sufficiently high safety factors, it

may remain operational for a period considerably beyond its design service life. Therefore, after the normative service life of a crane has expired, the residual life of its metal structure must be determined in order to establish whether the service life of the crane can be extended [1, 2]. The residual life of a hoisting machine is the calculated service period from the moment of expert assessment until the main components of the hoisting machine, namely the load-bearing metal structures, reach the ultimate limit state according to fatigue criteria. The residual life of a structure is determined by the degree of degradation of its material. Corrosion, fatigue, cracks, and deformation gradually reduce strength and safe service life.

Under modern operating conditions, accurate determination of the timing of specific technical inspection procedures and technical supervision for hoisting machines and mechanisms is essential. The aging and degradation of metal structures are among the main factors that determine the safety and service life of crane structures. During operation, crane metal structures are subjected to cyclic and variable loads, aggressive environments, and dynamic loading. This com-

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bination leads to progressive deterioration of load-bearing capacity. Non-destructive testing and numerical assessment can be combined to evaluate the technical condition of overhead cranes operating under difficult and corrosion-accelerating conditions [3], while structural health monitoring can combine strain and operational data to identify anomalies and estimate fatigue-life consumption [4].

2. Problem statement

Existing methodologies for assessing the residual life of hoisting machines are mainly based on the individual analysis of separate degradation mechanisms. Although such an approach may be considered conservative, it does not take into account the mutual interaction between defects. In practice, corrosion can reduce cross-sectional dimensions and introduce local stress concentration, thereby accelerating fatigue-crack development [5]. Crack-growth modelling that accounts for corrosion damage can be used to estimate the remaining fatigue life of corroded steel components [6]. Cracks, in turn, reduce the stiffness of the structure and lead to increased deflection. Consequently, degradation processes should be studied not separately, but as interconnected processes within an integrated framework. A comprehensive assessment of residual life is an integral indicator of the technical condition and accounts for the combined effects of several factors through a multi-parameter damage model. Within such a model, degradation mechanisms should be treated as interrelated parameters that form a unified level of accumulated damage in the structure, thereby enabling a more accurate prediction of residual life. The main objective of this study is to develop a methodology for assessing the residual life of overhead cranes based on an integrated diagnostic approach that accounts for the combined effects of corrosion wear, fatigue crack growth, and deformation of load-bearing elements, relying on diagnostic data, monitoring, and mathematical modelling.

Scientific novelty of the study

The scientific novelty of this study lies in the fact that, for the first time, corrosion wear, fatigue crack propagation, and deformation of load-bearing elements are integrated into a unified mathematical model within a system of coupled nonlinear differential equations for assessing the residual life of overhead cranes. Unlike existing approaches, the model describes the degradation mechanisms not independently, but with explicit consideration of their mutual interaction. In addition, an integral indicator $\Phi(t)$, based on the structural condition vector, is proposed for the comprehensive assessment of the technical condition, while diagnostic measurements, mathematical modelling, and residual-life prediction are integrated into a unified methodology. This approach makes it possible to identify the governing degradation mechanism and to predict residual life with improved accuracy.

3. Factors affecting the degradation of metal structures of overhead cranes

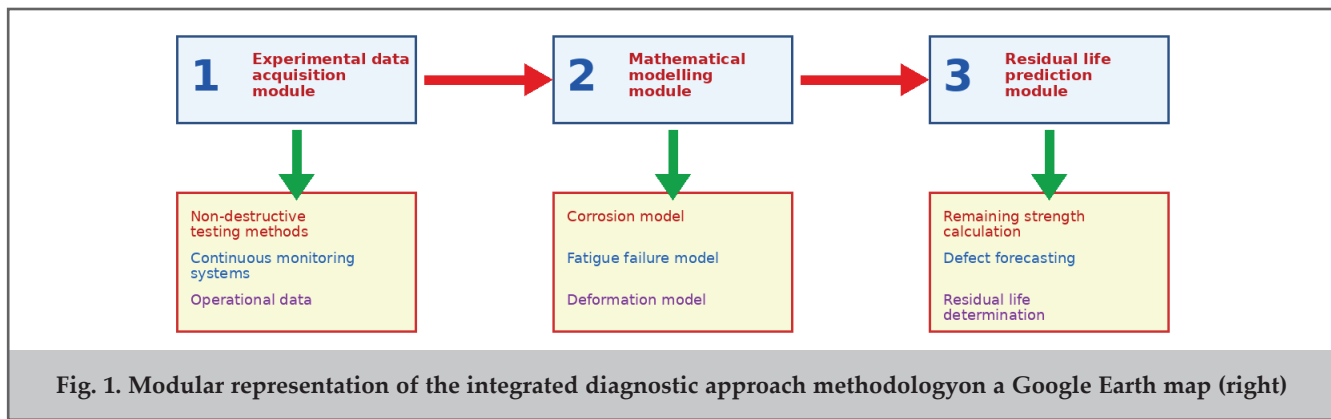
The metal components of a crane are subjected to fatigue loading, corrosion processes, structural changes, and technological defects, which accelerate physical and mechanical deterioration. Hoisting machines operate under cyclically varying loads. Variable-section supports of steel crane beams are susceptible to fatigue failure under cyclic loading [7]. Corrosion processes, including atmospheric corrosion and corrosion under protective coatings, reduce metal thickness, while pitting damage at joints can reduce metal strength and cause stress concentration. Premature deterioration may be associated with poor-quality welded joints, girder deflection, residual stresses introduced during manufacturing, and rolling defects. Manufacturing-related metallurgical defects and microcracks can provide crack-initiation sites in steel; this point is cited here only as a narrow material-defect background claim [8]. The most common defects observed in cranes can be classified according to the type of damage and the methods used for their detection. Table presents a classification of the main defects based on practical operational data, diagnostic studies, and normative documents. This classification serves as a basis for assessing the technical condition and selecting appropriate inspection methods.

Modern non-destructive testing (NDT) methods, including sensors, diagnostic systems, and analytical techniques, enable monitoring of material and structural condition without dismantling or damaging the structure. For overhead cranes operating under severe conditions, NDT can be integrated with numerical modelling to assess technical condition [3]. Visual and dimensional inspections, combined with ultrasonic thickness measurements, can be used to evaluate corrosion wear, detect deformation, assess welded joints, detect mechanical damage, and measure metal-wall thinning. Structural health monitoring can further combine strain measurements and operational data to support continuous assessment of structural response [4]. Acoustic Emission testing can record fatigue-crack activity and the dynamics of damage growth. Magnetic Particle Testing, used for ferromagnetic materials, detects magnetic-flux leakage at surface and near-surface cracks.

4. Methodology of the integrated approach

The proposed method is based on the integration of three main modules into a unified diagnostic and prognostic framework (fig. 1). The first module performs the acquisition of experimental data through periodic diagnostics and continuous monitoring systems. This module functions as the data acquisition component of the system and provides objective information on the current condition of the metal structure. The second module, which represents the central analytical component of the methodology, is responsible for parameter identification and mathematical modelling. At

Classification of the main defects				Table
Type of defect	Cause	Detection method	Hazard level	
Fatigue cracks	Cyclic loading	Ultrasonic Testing (UT), Acoustic Emission (AE)	High	
Corrosion	Atmospheric exposure	Visual inspection, Ultrasonic Testing (UT)	Medium	
Deflection	Overloading, corrosion, fatigue cracks	Geometric measurements	High	



this stage, data obtained from sensors and diagnostic devices are digitized and transformed into refined computational models that adequately describe the actual condition and the degradation processes occurring within the structure. Crane-oriented digital-twin approaches similarly integrate operational information with finite-element-based stress and life prediction [9, 10]. Recent crane-fatigue prognostic work has also used data-driven models to accelerate fatigue-life estimation, although such methods should not be interpreted here as validation of the present Paris-law-only formulation [11]. The third module functions as a forecasting component that predicts residual life by extrapolating the identified trends into the future on the basis of the developed mathematical models. Methodological analogues in other industrial assets show how laboratory and inspection data can be integrated with predictive analytics [12], and how remote monitoring can support condition-based and predictive maintenance [13]. These analogues are cited only for diagnostic and prognostic background, not as direct validation of the coupled physical equations used in this study. A schematic representation of this process, showing the data flow from empirical data acquisition to the generation of the final prediction, is presented in the following flow diagram.

5. Research methods for the degradation of metal structures

A number of mathematical and experimental methods, including stress calculation, fatigue damage analysis, and degradation modelling, are used for the quantitative assessment of metal-structure degradation and residual life. Based on a mathematical model describing the development of defects and changes in strength characteristics in the metal structure over time under the influence of operational loads, corrosion, and manufacturing defects, the residual life and failure probability of the metal structure are determined. The model is represented as the superposition of three subsystems:

1. Thickness reduction and local damage due to corrosion $\delta(t)$.
2. Fatigue crack propagation $\varepsilon(t)$.
3. Deformation defects $f(t)$.

The degradation process of the load-bearing elements of an overhead bridge crane is represented as a system of coupled differential equations describing corrosion wear, fatigue crack growth, and deformation increase. The residual life is defined as the time at which any one of these factors reaches its ultimate limit state. The obtained system of differential equations is solved as a Cauchy initial-value prob-

lem with prescribed initial values. The initial conditions are determined from the results of technical diagnostics and are adopted as follows:

$$\delta(0) = \delta_0; \quad \varepsilon(0) = \varepsilon_0; \quad f(0) = f_0$$

where δ_0 is the initial thickness of the element, ε_0 is the initial fatigue crack length detected during diagnostics, and f_0 is the initial structural deflection. These parameters are determined on the basis of ultrasonic thickness measurements, ultrasonic flaw detection, and geometric measurements.

The system of equations was solved analytically under simplifying assumptions. The corrosion equation was solved by direct integration, the crack-growth equation by the method of separation of variables, and the deflection equation by analytical substitution and evaluation of the corresponding definite integral. Based on the obtained analytical solutions, the time evolution of the degradation parameters was calculated, and the results were presented graphically.

Thickness reduction and local damage due to corrosion $\delta(t)$ are determined by the relative decrease in effective thickness or cross-section:

In the case of uniform corrosion:

$$\delta(t) = \delta_0 - v_{kor}t \quad (1)$$

where δ_0 is the nominal (initial) thickness; v_{kor} is the corrosion rate.

In differential form:

$$\frac{d\delta}{dt} = -v_{kor} \quad (2)$$

The weakening of the metal structure due to fatigue is associated with repeated loading cycles during lifting and lowering operations and the corresponding fluctuating bending stresses. In the present study, fatigue crack propagation is modelled exclusively using the Paris law. The crack growth rate $d\varepsilon/dt$ obtained from the Paris formulation is subsequently incorporated into the deflection equation, thereby establishing a mathematical coupling between the degradation mechanisms. According to the Paris law, the fatigue crack growth rate is expressed by the following equation:

$$\frac{d\varepsilon}{dt} = C \cdot N(t) [\Delta K(t)]^m \quad (3)$$

where ΔK is the stress intensity factor.

$$\Delta K = Y \cdot \Delta \sigma(t) \sqrt{\pi \varepsilon_{kr}} \quad (4)$$

where Y is a dimensionless geometric coefficient accounting for the crack geometry and configuration; $N(t)$ is the number

of load cycles per unit time and C and m are empirical Paris-law parameters characterizing fatigue crack propagation; and $\Delta\sigma(t)$ is the maximum bending stress in the critical section of the girder. The operating regime, load levels, and number of load cycles used to define $N(t)$ were adopted from the technical passport of the investigated crane (registration No. 18480) and were treated as input data characterizing its operating conditions. For the numerical example considered in this study, $C=1.2 \times 10^{-14}$ and $m=3$ were adopted as assumed calculation parameters for demonstrating the proposed methodology. These values were not obtained by experimental calibration for the investigated crane and should therefore not be interpreted as universal material constants. In practical applications, the Paris-law parameters should be determined for the specific material, welded condition, loading regime, stress ratio, environmental conditions, and unit convention through appropriate fatigue-crack-growth testing or validated material data [14]. The resistance of structural steels to degradation is also strongly influenced by material condition and environmental exposure; experimental studies on steels intended for aggressive service environments have shown that microstructural modification and heat treatment can significantly affect resistance to general corrosion, hydrogen cracking, and sulfide stress-corrosion cracking [15].

$$\Delta\sigma(t) = k_d \cdot k_{kr} \frac{M_{\max} \cdot h(t)}{2 \cdot J(t)} = k_d \cdot k_{kr} \cdot \frac{6M_{\max}(h_0 - v_{\text{kor}}t)}{(b_0 - v_{\text{kor}}t)(h_0 - v_{\text{kor}}t)^3 - (b_0 - 2\delta_{d0} + v_{\text{kor}}t)(h_0 - 2\delta_{q0} + v_{\text{kor}}t)^3} \quad (5)$$

where k_d is the dynamic coefficient accounting for the nature of load action and movement over an uneven surface; k_{kr} is the coefficient of constrained torsion and skewing of the crane; h_0 , b_0 are, respectively, the height and width of the girder cross-section; $J(t)$ is the moment of inertia of the girder with allowance for corrosion.

If corrosion reduces the thickness on all sides, then

$$b(t) = b_0 - v_{\text{kor}} \cdot t; \quad h(t) = h_0 - v_{\text{kor}} \cdot t; \\ \delta_d(t) = \delta_{d0} - v_{\text{kor}} \cdot t; \quad \delta_q(t) = \delta_{q0} - v_{\text{kor}} \cdot t$$

After thickness reduction due to corrosion, the moment of inertia is

$$J(t) = \frac{(b_0 - v_{\text{kor}} \cdot t)(h_0 - v_{\text{kor}} \cdot t)^3 - (b_0 - 2\delta_{d0} + v_{\text{kor}} \cdot t)(h_0 - 2\delta_{q0} + v_{\text{kor}} \cdot t)^3}{12} \quad (6)$$

Then the crack growth equation takes the following form:

$$\frac{d\varepsilon}{dt} = C \cdot N \cdot Y^m \cdot \left(k_d \cdot k_{kr} \frac{6M_{\max}(h_0 - v_{\text{kor}}t)}{(b_0 - v_{\text{kor}}t)(h_0 - v_{\text{kor}}t)^3 - (b_0 - 2\delta_{d0} + v_{\text{kor}}t)(h_0 - 2\delta_{q0} + v_{\text{kor}}t)^3} \right)^m \cdot (\sqrt{\pi \cdot \varepsilon})^m \quad (7)$$

For overhead cranes, the general expression for girder deflection is:

$$f = \frac{M_{\max} \cdot L^2}{12 \cdot E \cdot J(t)} \quad (8)$$

where L is the crane span; E is the modulus of elasticity of the bridge girder material.

Crack propagation, together with corrosion, has a significant influence on crane deflection. It reduces stiffness by affecting the moment of inertia of the girder cross-section. Therefore, when determining girder deflection, the additional deflection caused by the crack effect must also be taken into account.

Thus, taking into account the effects of both corrosion and crack propagation, the differential equation for deflection takes the following form.

$$\frac{df}{dt} = -\frac{M_{\max} \cdot L^2}{12 \cdot E \cdot J(t)^2} \cdot \left(\frac{dJ}{dt} \Big|_{\text{kor}} + \frac{dJ}{dt} \Big|_{\text{cat}} \right) = \frac{M_{\max} \cdot L^2}{12 \cdot E \cdot J(t)^2} \cdot \frac{1}{12} \left[v_{\text{kor}}(h^3 + 3bh^2) + \left(v_{\text{kor}} + 2 \frac{d\varepsilon}{dt} \right) \left[(h - 2\delta_q)^3 + 3(b - 2\delta_d)(h - 2\delta_q)^2 \right] \right] \quad (9)$$

where

$$\frac{dJ}{dt} = -\frac{1}{12} \left[v_{\text{kor}}(h^3 + 3bh^2) + \left(v_{\text{kor}} + 2 \frac{d\varepsilon}{dt} \right) \left[(h - 2\delta_q)^3 + 3(b - 2\delta_d)(h - 2\delta_q)^2 \right] \right]$$

System model of overhead bridge crane degradation (structural condition vector)

$$X(t) = \begin{bmatrix} \delta(t) \\ \varepsilon(t) \\ f(t) \end{bmatrix} \quad (10)$$

where $\delta(t)$ is the current thickness of the element; $\varepsilon(t)$ is the fatigue crack length; and $f(t)$ is the deflection of the main girder.

Taking into account the mutual interaction of degradation factors, the final system of equations for the degradation of the metal structure takes the following form:

$$\frac{dX(t)}{dt} = \begin{cases} \frac{d\delta}{dt} = -v_{\text{kor}} \\ \frac{d\varepsilon}{dt} = C \cdot N \cdot Y^m \cdot \left(k_d \cdot k_{kr} \frac{6M_{\max}(h_0 - v_{\text{kor}}t)}{(b_0 - v_{\text{kor}}t)(h_0 - v_{\text{kor}}t)^3 - (b_0 - 2\delta_{d0} + v_{\text{kor}}t)(h_0 - 2\delta_{q0} + v_{\text{kor}}t)^3} \right)^m \cdot (\sqrt{\pi \cdot \varepsilon})^m \\ \frac{df}{dt} = \frac{M_{\max} \cdot L^2}{12 \cdot E \cdot J(t)^2} \cdot \frac{1}{12} \left[v_{\text{kor}}(h_0^3 + 3b_0h_0^2) + \left(v_{\text{kor}} + 2 \frac{d\varepsilon}{dt} \right) \cdot \left[(h_0 - 2\delta_{q0})^3 + 3(b_0 - 2\delta_{d0})(h_0 - 2\delta_{q0})^2 \right] \right] \end{cases} \quad (11)$$

The directions of interaction incorporated into the model are defined on the basis of the underlying physical degradation mechanisms. Corrosion affects both fatigue crack propagation and deflection through the reduction in cross-sectional thickness, whereas crack propagation contributes to increased deflection through the associated reduction in structural stiffness. The reverse influence of deformation on crack propagation is not introduced as an independent

functional relationship in the adopted Paris-law formulation, since deformation is not included as a separate input variable in the crack-growth equation.

Thus, the degradation mechanisms in the proposed model are not evaluated as fully independent processes but are mathematically coupled. The corrosion-induced change in thickness, $\delta(t)$, enters the crack-growth formulation, while the crack growth rate, $d\epsilon/dt$, is subsequently incorporated into the deformation equation. At the same time, the effect of corrosion on deformation is accounted for through the corrosion-induced changes in the geometric and stiffness characteristics of the cross-section. Accordingly, the resulting system represents an interconnected degradation model:

$$d\delta/dt = F_1(\delta) \quad d\epsilon/dt = F_2(\delta, \epsilon) \quad df/dt = F_3(\delta, \epsilon, d\epsilon/dt)$$

A similar need to account for interacting operational effects has been reported in other industrial systems, where vibration, erosion-corrosion wear, and changing operating conditions may coexist and complicate technical-condition assessment [16]. Such evidence is used here only as a methodological analogue and not as direct validation of the proposed crane model.

This system of equations is not merely a mathematical expression; it is also a working tool for predicting service life and optimizing materials and structures under complex combined loading, that is, under the simultaneous influence of several degradation factors. By accounting for the interactions between degradation mechanisms incorporated into the mathematical model, this formulation helps to avoid unsafe or insufficiently justified engineering decisions.

Residual life is determined according to the most critical failure factor, although it can be formally expressed as a unified function:

$$T_{resurs} = \min(T_{cor}, T_{cat}, T_{def}) = \min \left(\frac{\delta_{eff} - \delta_{min}}{v_{korr}}, \frac{2 \cdot \left(\epsilon_{kr}^{\frac{1-m}{2}} - \epsilon_0^{\frac{1-m}{2}} \right)}{(2-m) \cdot C \cdot N \cdot (\Delta\sigma(t))^m \pi^{\frac{m}{2}}}, \frac{f_{heddi} - f_0}{f_{heddi}} \right) \quad (12)$$

To quantitatively assess the overall condition of the technical system on the basis of diagnostic and monitoring results, a scalar indicator of technical condition is sometimes required:

$$\Phi = \max \left[\frac{\delta_0 - \delta(t)}{\delta_0 - \delta_{min}}, \frac{\epsilon(t)}{\epsilon_{kr}}, \frac{f(t)}{f_{heddi}} \right] \quad (13)$$

Then

$$T_{resurs} = (1 - \Phi) \cdot T_{lay} \quad (14)$$

If $\Phi < 1$, the crane remains operable; if $\Phi = 1$, this condition corresponds to the boundary of the limit state (end of service life).

In the present study, the problem of determining the residual life of a general-purpose overhead bridge crane belonging to the Reinforced Concrete Products Division (RCPD) of the SOCAR Oil and Gas Construction Trust was examined using various methods and comparing the obtained life assessment results. The overhead bridge crane under consideration was manufactured by the Oleksandriia Hoisting and Transport Equipment Plant of Ukraine. It has a lifting capacity of 16/3.2 tons, factory No. 17080, and registra-

tion number 18480. The crane was installed at an enterprise of the Oil and Gas Construction Trust after the expiration of its service life and is used for loading and unloading piece loads.

The initial parameters used in the calculations were obtained from the results of technical diagnostics. These include the initial thickness of the element, corrosion rate, initial crack length, initial deflection, mechanical properties of the material, and geometric parameters of the structure. These parameters were adopted as the initial data for the analytical solution. For the numerical implementation, the crane girder was represented using its span and principal cross-sectional dimensions, while the operational loading was introduced through the maximum bending moment used in the stress and deflection calculations. The initial technical state of the model was defined by the measured values of thickness, crack length, and girder deflection. A complete computational representation also requires the model geometry, loading conditions, and boundary conditions to be explicitly specified in order to ensure interpretability and reproducibility. This general modelling requirement has also been emphasized in numerical studies of industrial equipment, where the definition of computational and boundary conditions was shown to affect the reliability of the calculated results [21].

It should be emphasized that the diagnostic measurements are used to characterize the current technical condition of the structure and to establish the initial conditions of the mathematical model. The subsequent evolution of corrosion, fatigue crack propagation, and deflection over the following years does not represent directly measured experimental data; rather, these quantities are predicted using the developed mathematical model. Consequently, a single diagnostic measurement cannot, by itself, confirm the long-term predictive accuracy of the model. Experimental verification of the long-term predictions requires repeated diagnostic measurements performed at different stages of operation. In this context, continuous crane-girder monitoring systems based on strain measurements and digital-twin models have been proposed to track stress and deformation states in real time and to provide a more continuous basis for structural-condition assessment [17].

The methodology for assessing the residual life of the overhead bridge crane was based on the application of a non-destructive magnetic control method for evaluating the stress-strain state of the metal. The main controlled parameters of the bridge crane metal structure were corrosion, cracks, and deflection of the main girders. To measure the degree of corrosion in characteristic areas of the bridge crane, an LDC1614 magnetic thickness gauge was used; to detect internal cracks and defects in welded joints, a USN UD-2I-P-46 ultrasonic flaw detector was used; and to measure the deflection of the main girder, a laser level was used. Measurement results: corrosion rate $v_{korr} = 0.1$ mm/year; crack depth $\epsilon = 2.0$ mm; and girder deflection $f = 8$ mm. Recent research on overhead-crane structures has also demonstrated the applicability of advanced non-destructive screening techniques for fatigue-crack detection, including infrared thermographic testing combined with image-based classification methods for crane runway girders [18].

The deflection value obtained using the laser level was adopted as the initial deflection parameter f_0 of the structure in the mathematical model. It should be noted that, within the scope of the present study, variations in rail level, set-

tlement of the supports, and geometric imperfections of the crane runway were not measured separately and therefore were not fully isolated from the overall measurement result. Accordingly, the measured value is treated as an initial parameter f_0 characterizing the current geometric condition of the crane rather than as an experimentally isolated measure of main-girder deformation alone.

Figure 2 presents time and phase diagrams characterizing the interrelationships between corrosion, crack development, and deflection processes. The graphs make it possible to assess changes in the technical condition of the structure during its service life and to evaluate the influence of individual degradation mechanisms on the overall load-bearing capacity.

Figure 2a shows the graph reflecting the decrease in thickness over time due to corrosion. Since the corrosion rate is assumed to be constant, the change in thickness has a linear character. According to the calculations, the minimum allowable thickness is reached after 20 years, which corresponds to the onset of the critical corrosion state.

Figure 2b shows the change in crack length over time. Crack development is modelled according to the Paris law. Although the crack growth rate is relatively low at the initial stage, the process accelerates as crack length increases due to the increase in the stress intensity factor. The calculations show that the critical crack length is reached after approximately 2.66 years.

Figure 2c shows the change in structural deflection over time. As can be seen from the graph, deflection increases as a result of thickness reduction and weakening of the stiffness

of the load-bearing elements. According to the calculations, the allowable deflection limit is reached after approximately 4.31 years.

The relationship between crack length and thickness is shown in figure 2d. As thickness decreases, the cross-sectional area and stiffness decrease, resulting in an increase in the stress intensity factor and acceleration of crack development. This dependence confirms the existence of a close mutual interaction between the corrosion and crack mechanisms.

The graph shown in figure 2e characterizes the dependence of deflection on thickness. A decrease in thickness leads to a reduction in the moment of inertia of the cross-section, which results in increased deflection. This dependence indicates that corrosion is one of the main causes of stiffness loss in the structure.

The graph shown in figure 2f reflects the relationship between deflection and crack length. As can be seen from the graph, crack growth reduces the effective cross-sectional area and consequently lowers the stiffness of the structure. Therefore, deflection increases as crack length increases. The nonlinear character of the graph indicates that, in the final stages of degradation, even small crack increments can cause a noticeable increase in deflection.

Overall, the analysis shows that the most dangerous degradation mechanism for the structure under consideration is crack development. The time to the critical state for cracking is approximately 2.66 years, which is significantly shorter than the critical times for deflection (4.31 years) and corrosion (20 years). Therefore, the residual life of the structure is primarily limited by the crack propagation process.

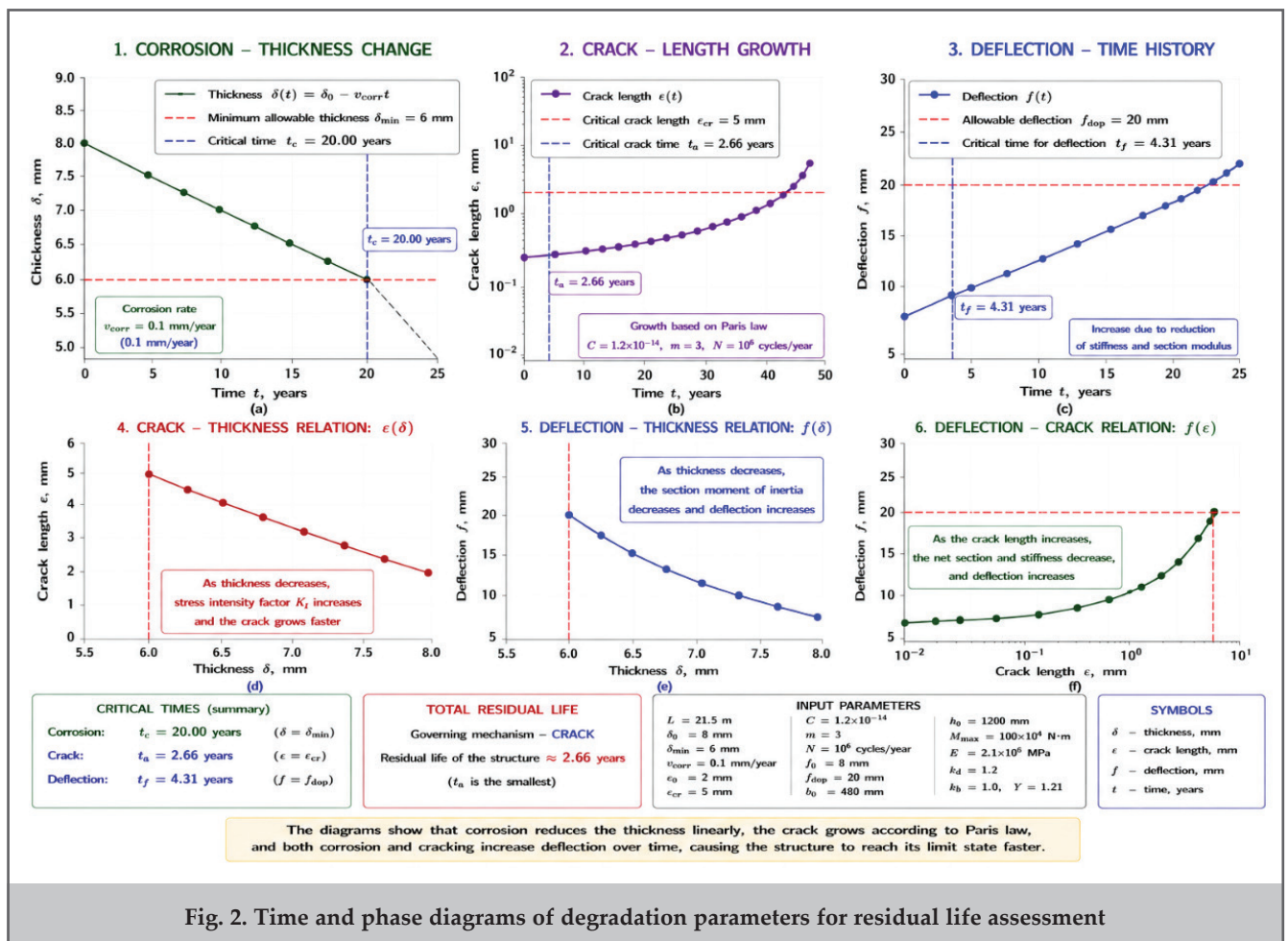


Fig. 2. Time and phase diagrams of degradation parameters for residual life assessment

6. Discussion of results

To quantitatively assess the effect of the proposed integrated approach, three computational scenarios were compared in which the degradation mechanisms were incorporated progressively: a corrosion-only model, a coupled corrosion-crack model, and a full model accounting for corrosion, crack propagation, and deformation. Under identical initial and loading conditions, the corrosion-only model reached the critical state after 20 years. When corrosion and crack propagation were considered jointly, the predicted residual life decreased to 2.66 years. The full model incorporating corrosion, crack propagation, and deformation also yielded a residual life of 2.66 years. This result is explained by the fact that the crack reaches its critical limit after 2.66 years, whereas the allowable deflection limit is reached only after approximately 4.31 years. Thus, although inclusion of the deformation mechanism does not alter the governing degradation mechanism in this particular numerical example, it provides a more comprehensive representation of the structural condition and enables the relative contributions of the individual degradation mechanisms to be evaluated.

The diagnostic measurements presented in this study were used to establish the initial conditions of the model and should not be interpreted as an independent experimental validation of its long-term predictions. Full validation of the proposed model would require comparison of the predicted results with repeated diagnostic measurements obtained at different stages of service, together with quantitative assessment using relative error, root mean square error (RMSE), and other appropriate goodness-of-fit measures. This con-

stitutes a limitation of the present study and an important direction for future research. Recent crane-girder research under moving-load conditions further demonstrates that structural damage identification and health assessment can be evaluated through experimentally verified crack tests combined with vibration-response analysis, highlighting the importance of independent measurement data in model-based condition assessment [19].

It should be noted that the numerical example presented in this study is intended to demonstrate the operating principle of the proposed method. The proposed model is not specific to the particular 16/3.2-ton overhead crane considered in the study. The structure of the model is general and can be applied to overhead cranes of different types and operating under different service conditions by modifying the input parameters, including lifting capacity, span, structural dimensions, material properties, corrosion rate, operational loads, and diagnostic data. Therefore, the mathematical formulation provides a basis for potential application of the method to overhead cranes with different structural and operating characteristics, provided that the corresponding input parameters are appropriately defined. The numerical example presented herein serves as a computational demonstration of the proposed methodology.

From a practical life-extension perspective, recent studies on existing crane runway girders have also emphasized condition-specific strategies for strengthening and repairing fatigue-damaged welded components, including structures with visible cracking [20]. This reinforces the importance of linking residual-life assessment with inspection and maintenance decision-making.

Conclusions

1. A methodology based on an integrated diagnostic approach has been developed for assessing the residual life of overhead cranes, taking into account the combined effects of corrosion wear, fatigue crack growth, and increasing deformation in load-bearing elements.
2. A system of differential equations describing the time-dependent evolution of damage has been formulated, and an integral indicator $\Phi(t)$, which determines the moment of residual life exhaustion of the structure, has been introduced on this basis.
3. On the basis of numerical values, it has been established that, under moderate operating regimes, the main factor limiting residual life is the mechanism of fatigue crack propagation. Under severe operating regimes and in highly aggressive corrosive environments, a combined failure mechanism develops, characterized by the mutual amplification of crack formation and deformation.
4. It has been determined that the use of the proposed diagram enables rapid assessment of the technical condition of overhead cranes, supports the prioritization of repair measures, and allows residual life prediction without performing labor-intensive detailed calculations.
5. The obtained results can be used in industrial safety assessment, the development of technical condition monitoring programs, and engineering decision-making aimed at extending the service life of overhead cranes.

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