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ROBUST DESIGN OF METAL STRUCTURES FOR MINIMIZING CORROSION RISKS

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Abstract. The article addresses the reduction of risks associated with the potential emergence of industrial hazards caused by decreased reliability of corrosion protection systems for structures, within the framework of robust structural design (**RDCPS** – *Corrosion Protection System under Robust Structural Design Conditions*). The proposed approach is based on the development of robust (resilient to disturbing external influences) methods for designing primary and secondary corrosion protection measures for metal structures. In order to improve structural operation at all stages of the life cycle, a diagnostic and maintenance technology is substantiated. Enhanced survivability and resistance to aggressive operational environments are achieved through effective robust design strategies for both primary and secondary protection of metal structures against corrosion. The proposed methodology contributes to the advancement of current standards (EN 1990) by incorporating principles of robust design. It is established that these requirements aim to ensure the quality of metal structures and are implemented through limit state calculations using partial safety factors (EN 1991). Structural load-bearing capacity and durability are ensured in accordance with the provisions of EN 1993. Characteristic values of metal structure quality indicators, protective coatings (EN ISO 12944, EN 1461), and materials (EN 1993-1-4) are applied. The methodology proposed herein is aimed at minimizing risks during the creation of metal structures and reducing the extent of damage due to corrosion loss, which remains a highly relevant objective in the construction industry.

Keywords: metal structures, durability, robust design, corrosion protection, corrosion resistance

Problem Statement. Ensuring technological safety in the construction sector and preventing the occurrence of accidents and emergency situations of industrial origin constitute the foundation for establishing safe living conditions and represent an integral component of the functioning of the construction industry as a whole [1].

The inadmissibility of a steady decline in the level of safety and reliability of critical construction facilities-particularly during the operation of civil and industrial buildings, lifting mechanisms, and supporting structures-along with the unsatisfactory condition of equipment and engineering networks operating in industrial environments and posing potential threats to human life, necessitates the adoption of a comprehensive approach. Such an approach is essential for solving the problem of ensuring technological safety and mitigating risks, utilizing the potential capabilities and advantages of robust design methodology.

The reliability requirements for metal structures of load-bearing and lifting mechanisms are driven by the need to reduce risk levels on a methodological basis through the application of a process-based approach, as stipulated at the international level by ISO 9001 / IEC 300-1 standards. The application of robust design principles allows for the formulation and implementation of management tasks related to service life planning, reliability assurance, and justification of sequential stages for assessing the survivability of building metal structures. These tasks are carried out on the basis of robust design principles, continuous improvement strategies, and control of technological measures during project implementation [2].

Analysis of Recent Research and Publications. An analysis of current requirements for the means and methods of corrosion protection of metal structures, along with a systematization of classification features of aggressive environments and indicators of corrosion resistance of steels, protective coatings, and structural joints-taking into account the nature and degree of environmental aggressiveness-demonstrates that the issue of insufficient service life of structures operating in varying degrees of corrosive environments is largely due to the lack of a methodological basis for design and technological decisions related to primary and secondary corrosion protection based on reliability indicators and safety conditions for building facilities [3, 4].

Research in this area is aimed at enabling service life extension of structures by applying methods that ensure the durability of structural materials, while simultaneously emphasizing rational design, the development and use of expressive architectural forms, and the application of volumetric-planning and technological solutions. The integration of reliability conditions and structural rationality with the parallel development of durability assurance methods is achieved through the implementation of technological safety principles, in line with total quality management (TQM) methodology and risk reduction strategies.

A significant level of potential risk arises when structural components remain for extended periods in aggressive environmental conditions, which poses a threat to the quality of lifting equipment as well as buildings and structures themselves. This, in turn, leads to heightened demands for improving the operational performance of metal structures [5, 6].

Identification of Previously Unresolved Components of the General Problem. The life cycle of metal structures used in cargo cranes spans a significant time interval. To obtain reliable information and data based on statistical analysis of damage, defects, and imperfections, a prolonged observation period is necessary, during which the collection, processing, accumulation, and storage of data are complicated. Under these circumstances, reliability characteristics can be determined based on the properties of the structure and the operational environment-features that exhibit mass characteristics and are evaluated using statistical methods. These include: structural material properties; magnitudes of external effects (frequently repeating and recorded); geometric parameters of buildings and structures and their structural elements; and characteristics of joints, connections, and load-handling mechanisms.

In reliability theory, these parameters are referred to as **basic variables** X1, X2,...Xi, which cannot be mathematically represented as random variables or stochastic processes and must be obtained through **in-situ investigations**. The **limit state** of a structure – defined as the presence of defects, imperfections, or damage-is described as a function of these basic variables [6, 7]. To solve the main task of reliability theory for load-bearing structures and to theoretically determine the **probability of failure occurrence**, initial statistical data on the basic variables Xi are used.

The condition of dismantled structures, considering the most unfavourable combinations of technological effects and the condition of individual elements, has been examined in accordance with a **methodological approach** that substantiates the composition and structure of **durability parameters** for controlling technological safety through risk reduction. This demonstrates the feasibility of **ensuring structural resources** through a combined application of analytical methods-enabled by a rational technological strategy and the use of advanced planning tools to promote construction process efficiency [8].

Regardless of the structural form **Sb** it is necessary to determine the initial conditions and internal states of the system. Developing a verification program requires an analysis of the structure of the object under study-both in its **operational state** and under **potential failure conditions** of structural elements and mechanisms. The formalization of this analysis involves describing possible defects and damage (e.g., presence of imperfections, flaws, degradations) resulting from service life, disassembly, transportation, and storage-factors that are largely determined by the **failure intensity of structural components**.

The introduction and definition of input functions for defective elements are carried out by enumerating potential imperfections-such as defects and damage in steel structures of cranes, changes in technical properties of machines and mechanisms caused by prolonged use, environmental conditions during storage, and construction site factors. The object is described in terms of **L components**. If **Si** is the number of possible individual imperfections of the **j-th** component, then the total number **M** of potential imperfections for the object under control is calculated as follows:

- If individual defects are present (each part contains one imperfection):

$$M1 = \sum_{i=1}^{L} Sj \tag{1}$$

- If individual parts contain one or multiple defects (some components contain one defect):

$$M2 = \prod_{i-1}^{L} (1 + Sj) - 1 \tag{2}$$

- For multiple imperfections within components and multiple imperfections across the entire object (a component contains more than one defect):

$$M3 = 2^{M1} - 1 \tag{3}$$

In cases where a real-world operational object is available, its **technological purpose** (specifically, the order of data input at the design stage), potential imperfections, and implemented functions can be determined, along with the methodology for **diagnosing the state of structures and joints**.

The **risk assessment procedure** for the operation of **lattice-type metal structures** and the interaction of internal parameters with major external environmental influences is presented using a **structural diagram**. This diagram defines the state of the model at any moment in time **t** through input variables **Fi** _i, internal variables **IN**i and output variables **OPi** where inputs and internal variables are treated as **independent variables**, and outputs are their **functional results** [9].

A graphical representation of this **diagnostic process** during the **monitoring procedure** for dismantling a tower crane structure is shown in the form of a **block diagram (Figure 1)**.

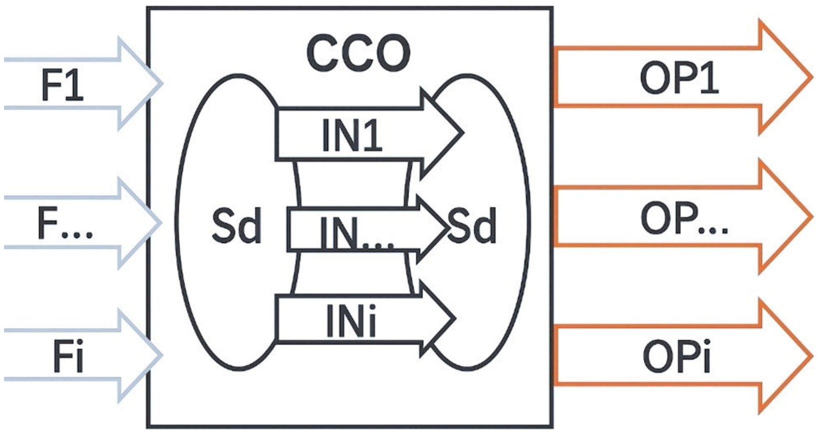


Fig. 1. Block diagram for monitoring the state parameters of the procedure used for decision-making in robust structural design and risk factor evaluation

The conditional decomposition of the control object (CCO) into its components is associated with a number of objective conditions and subjective assumptions. The selected components **Sb** represent structures, parts, and joints that form independent systems or elements (e.g., joints, members, metallic structures, or engineering and technological equipment, tools, etc.).

The control object, as a **logical system**, can be represented graphically, analytically, through a physical model, or in another virtual form suitable for processing by computational methods [10-13].

Formulation of Research Goals and Objectives. The aim of this research is to identify the factors affecting the **safety of structural and joint mechanisms**, analyze and systematize data related to **execution processes in spatially constrained construction environments**, and determine optimal design options from an industrial enterprise's perspective. The research further accounts for the **forecasting and progression of defects, imperfections, and structural damage**. A detailed study was conducted focusing on the operational behavior of a **cargo crane** in the constrained space of an **active industrial environment**. The proposed methodology is aimed at minimizing structural risks and addresses an urgent task in the field of construction.

More specifically, the objective of this work is to identify the factors that influence the **technological safety of operational processes** involving structural components and crane mechanisms, to analyze and systematize data related to execution procedures in the **limited space of a production facility**, and to determine optimal crane dismantling scenarios that provide the most benefit for the enterprise. The study involved analysis of crane operations in the **agglomeration conditions of the metallurgical industry**. The methodology is targeted at minimizing technological risks in structural processes, which is a critical task in the field of **civil engineering**.

Main Material and Results. Changes in the **qualitative characteristics of metal structures** under conditions of irreversible stochastic degradation processes emerge during both the erection and operation phases of buildings and structures. **Material wear** is associated with the emergence and accumulation of **corrosion damage** in metal elements and the **deterioration of protective coatings**. The result is a degradation of geometric properties of cross-sections, a decline in mechanical properties of materials, and ultimately, a loss of operational performance.

When structuring the data related to the operational condition of metal structures and identifying the **level of corrosion hazard**, the parameters of technical condition are described using **QFD (Quality Function Deployment)** methods. The structural description is implemented in the form of individual matrices, based on the principles outlined in [11–14]. The description follows a **structural-organizational model** using the House of Quality (HQ) approach (see **Figure 2**) in the form of a **target technological function** of the object under study.

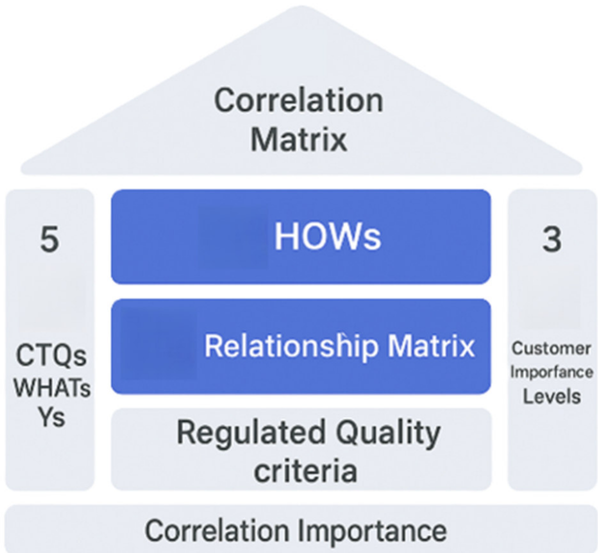


Fig. 2. Structural-organizational model HQ:
1 – Correlation Matrix (optional) - matrix of correlation coefficients between characteristics; 2 – HOWs, Xs- - technical characteristics; 3 – Customer Importance Levels per CTQ (Critical to Quality) - standardized customer-driven quality criteria; 4 – Relationship Matrix - matrix of technological parameters and constraints; 5 – CTQs, WHATs, Ys - technological function of the object; 6 – Calculated Importance Values of the HOWs - target technological function of the object under investigation

Parametric Characteristics of the Structural Components of the HQ Model. The parametric characteristics of the structural components of the HQ model include:

1 – technological function;

2 – production-technological characteristics of buildings under actual operating conditions and environmental influence;

3 – Relationship Matrix of technological parameters and constraints;

4 – normalized quality criteria;

5 – correlation matrix - a matrix of correlation coefficients between technical characteristics and performance parameters;

6 – target technological function.

Standardized indicators of **reliability and durability** are integrated. Functionally interacting technical characteristics and operational parameters are correlated within the matrix of system performance, ensuring consistency in evaluating the robustness of corrosion protection characteristics **RDCPS** – Corrosion Protection System under Robust Structural Design Conditions [15].

Analytical Modeling of Corrosion Wear of Metal Structures

The analytical expression describing the actual condition of metal structural elements under corrosion wear, [**F**(*N*), g/m^2], is obtained using an **active experimental design** through **fractional factorial replication** 2^{15-10}. The derived relationship reflects a parametric dependency under programmable impact scenarios involving variations in structural shape parameters (***j***) and corrosion exposure factors (***i***):

$$\Phi(N) = A_i + A_j + A_{i,j} + A_{i,j-1}, \tag{4}$$

$$A_{i,j} = a_0 \sum_{i=0}^{i=N} \sum_{j=0}^{j=L} a_{i,j} \Big/ T_k, \tag{5}$$

where:

$A_{i(j)}$ - system variable representing corrosion losses, g/m^2·year;

$a_{i(j)}$ - weighting factor characterizing the structural form parameters (*i, j*);

a_0 - corrosion losses of S235 steel during accelerated corrosion testing, (g/m^2);

T_k - time interval corresponding to stabilized corrosion losses, in years.

Expert Evaluation of the Generalized Indicator of Coating Protective Properties. The expert evaluation of the generalized indicator of the protective properties of coatings (A_z) is given by the following expression:

$$A_z = \sum_{i=1}^{i=N} B_i X_i, \tag{6}$$

where:

B_i - weighting coefficient for the type of degradation;

X_i - relative assessment score of the *i* -th degradation mode.

The evaluation results of the indicators based on formulas (2) and (3) allow for determining the normative service life of the protective coating system (PCS):

$$T_Z = \Delta P(N) / A_n, \tag{7}$$

where: *P(N)* - corrosion loss of unprotected steel corresponding to the number of accelerated test cycles *N* up to the established failure threshold, g/m^2.

Application of Monitoring Results for Robust Design Solutions

The monitoring results of diagnostic parameters used to support decision-making in the robust design of structures and associated corrosion risk factors were obtained under real industrial operating conditions.

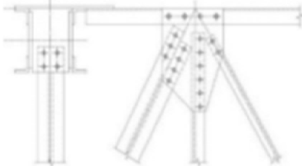
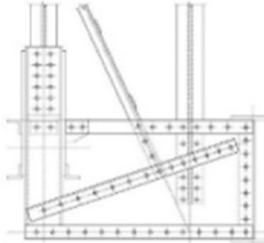
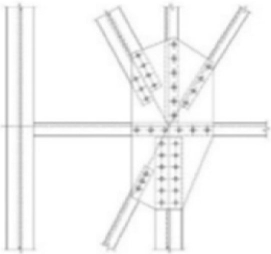
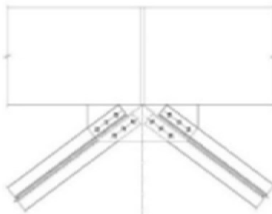
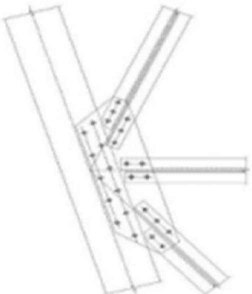
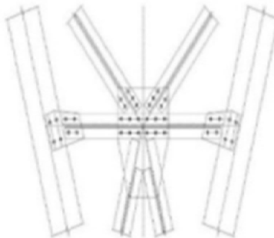
The subject of the study consisted of **lattice-type steel structures** forming the **span system of a gantry crane** operating in the environment of an industrial facility (Figures 3, 4).

The parameters of quality indicators - including those for metal structures, structural solutions of nodal joints, and the protective properties of anticorrosion coatings - were defined in accordance with the framework of the proposed methodology (see **Table**).

Fig. 3. Support structure of the crane under industrial site conditions

Fig. 4. Upper bracing trusses of the crane's span structure

Table 1 Expert Assessment of the Condition (CCSRI[1] – Corrosion Control System Reliability Index)

№	Structural Components	Structural Diagram of Elements	CCSRI Parameters	No.	Structural Components	Structural Diagram of Elements	CCSRI Parameters
1			$T_{ef} = 25$ $\gamma_{f} = 0{,}426$ F_e=3,13	**4**			$T_{ef} = 32$ $\gamma_{f} = 0{,}544$ F_e =1,34
2			$T_{ef} = 21$ $\gamma_{f} = 0{,}68$ F_e =0,51	**5**			$T_{ef} = 28$ $\gamma_{f} = 0{,}569$ F_e =0,81
3			$T_{ef} = 21$ $\gamma_{f} = 0{,}674$ F_e =0,36	**6**			$T_{ef} = 21$ $\gamma_{f} = 0{,}68$ F_e =0,51

1 - **CCSRI Parameters** – Parametric coefficients characterizing the corrosion resistance of metallic joints and structural components, taking into account their geometric configurations and connection forms under typical service environments of a construction facility.

Conclusions

The presented structural representation of the robust design procedure and the accompanying visualization of the decision-making monitoring process ensure the integrity conditions of metal structures, joints, and the safety of work execution. This is achieved through detailed identification and characterization of specific deficiencies or nonconformities in technological implementation.

The proposed methodology enables the identification and evaluation of risks during the planning phase of design decisions and structural modelling. This approach creates opportunities for the economic optimization of material expenditures, aimed at reducing the overall construction costs. The effectiveness of the methodology is enhanced when decommissioning several research objects that were previously engaged in the production process [16].

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РОБАСТНЕ ПРОЕКТУВАННЯ МЕТАЛЕВИХ КОНСТРУКЦІЙ ПРИ МІНІМІЗАЦІЇ РИЗИКІВ КОРОЗІЙНОЇ НЕБЕЗПЕКИ

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Анотація.

Статтю присвячено зниженню ризиків можливого виникнення виробничих небезпек, пов'язаних зі зниженням надійності систем протикорозійного захисту конструкцій в умовах робастного проектування конструкцій (СПЗРК). Запропонований підхід базується на розвитку робастних (стійких до збурювальних зовнішніх впливів) методів проектування заходів первинного та вторинного захисту металевих конструкцій від корозії. Для підвищення ефективності експлуатації споруд на всіх етапах їх життєвого циклу обґрунтовано технологію діагностики та технічного обслуговування. Зростання живучості та стійкості до агресивних експлуатаційних середовищ забезпечується ефективними методами робастного проектування систем первинного та вторинного протикорозійного захисту металоконструкцій. Розробку спрямовано на розвиток положень чинних норм EN 1990 з використанням принципів робастного проектування. Встановлено, що ці вимоги спрямовані на забезпечення якості металоконструкцій і реалізуються в розрахунках за методом граничних станів із використанням часткових коефіцієнтів надійності (EN 1991). Забезпечення несучої здатності та довговічності відбувається відповідно до вимог стандарту EN 1993. При цьому використовуються характеристичні значення показників якості металоконструкцій, захисних покриттів (EN ISO 12944, EN 1461) і матеріалів (EN 1993-1-4).

Запропонована методологія дозволяє ідентифікувати та оцінювати ризики на етапі планування проектних рішень та структурного моделювання. Такий підхід створює можливості для економічної оптимізації витрат на матеріали з метою зниження загальних витрат на будівництво. Ефективність методології підвищується при виведенні з експлуатації декількох дослідних об'єктів, які раніше були задіяні у виробничому процесі.

Ключові слова: металеві конструкції, довговічність, робастне проектування, протикорозійний захист, корозійна стійкість.