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INTEGRATED TECHNICAL CONDITION ASSESSMENT OF AGING PORT HANDLING EQUIPMENT FOR SERVICE LIFE EXTENSION

ІНТЕГРОВАНЕ ОЦІНЮВАННЯ ТЕХНІЧНОГО СТАНУ ПОРТОВОГО ПЕРЕВАНТАЖУВАЛЬНОГО ОБЛАДНАННЯ ДЛЯ ПРОДОВЖЕННЯ СТРОКУ ЕКСПЛУАТАЦІЇ

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Abstract. The operation of port handling equipment that has been in long-term service under marine conditions is accompanied by intensive cyclic loading, corrosion, fatigue damage, deformation, and mechanical wear. The integration of engineering diagnostics, condition-based maintenance, structural assessment, and residual service-life evaluation provides a reliable basis for decision-making regarding repair, strengthening, modernization, controlled operation, and service-life extension. *Purpose*. To investigate modern European approaches to maintenance management of aging port handling equipment and assess their applicability to extending crane service life under long-term marine conditions. *Method*. The study considers the principal degradation mechanisms identified during technical inspections, including corrosion, fatigue cracking, permanent deformation, and wear of structural and mechanical components. The obtained data are used to assess technical condition, structural integrity, operational safety, and residual service life. The application of Condition-Based Maintenance and Structural Health Monitoring is also considered. *Results*. The analysis confirms that corrosion, fatigue, deformation, and wear are the main factors limiting the service life of aging port cranes. An integrated maintenance approach improves maintenance planning, reduces operational risks, and supports economically justified decisions on repair, modernization, and service-life extension. *Scientific novelty*. An integrated engineering framework combining technical inspection, structural assessment, residual-life evaluation, condition-based maintenance, and digital monitoring is proposed. *Practical importance*. The approach can be applied by port authorities, maintenance organizations, classification societies, and engineering companies to improve maintenance planning, enhance safety, reduce unexpected failures and maintenance costs, and extend the service life of existing port handling equipment.
Key words: port handling equipment; aging cranes; technical condition assessment; condition-based maintenance; structural integrity; residual service life; non-destructive testing; structural health monitoring.

Анотація. Експлуатація портового перевантажувального обладнання, що тривалий час працює в морських умовах, супроводжується інтенсивним циклічним навантаженням, корозією, втомними пошкодженнями, деформаціями та механічним зношуванням. Поєднання інженерної діагностики, технічного обслуговування за фактичним станом, оцінювання конструкцій і залишкового ресурсу створює надійну основу для прийняття рішень щодо ремонту, підсилення, модернізації, контрольованої експлуатації та продовження строку служби. *Мета*. Дослідити сучасні європейські підходи до управління технічним обслуговуванням портового перевантажувального обладнання тривалої експлуатації та оцінити можливість їх застосування для продовження строку служби кранів у морських умовах. *Методика*. Розглянуто основні механізми деградації, виявлені під час технічних обстежень: корозію, втомне тріщиноутворення, залишкові деформації та зношування конструктивних і механічних елементів.Також розглянуто застосування технічного обслуговування за фактичним станом і моніторингу технічного стану конструкцій. *Результати*. Підтверджено, що корозія, втома, деформації та зношування є основними чинниками, що обмежують строк служби портових кранів тривалої експлуатації. Комплексний підхід підвищує ефективність планування технічного обслуговування, знижує експлуатаційні ризики та забезпечує економічно обґрунтовані рішення щодо ремонту, модернізації та продовження строку служби. *Наукова новизна*. Запропоновано комплексну інженерну модель, що поєднує технічне обстеження, оцінювання конструкцій, визначення залишкового ресурсу, технічне обслуговування за фактичним станом і цифровий моніторинг. *Практична значимість*. Підхід може застосовуватися портовими адміністраціями, ремонтними організаціями, класифікаційними товариствами та інжи-

ніринговими компаніями для вдосконалення планування технічного обслуговування, підвищення безпеки, зниження ризику відмов і витрат на обслуговування та продовження строку служби наявного портового перевантажувального обладнання.

Ключові слова: портове перевантажувальне обладнання; крани тривалої експлуатації; оцінювання технічного стану; технічне обслуговування за фактичним станом; конструкційна цілісність; залишковий ресурс; неруйнівний контроль; моніторинг технічного стану.

PROBLEM STATEMENT

Port handling equipment is a critical component of maritime transport infrastructure, ensuring loading, unloading, and transshipment operations in seaports. The operational reliability of quay cranes, floating cranes, portal cranes, and other lifting machines directly affects the continuity and efficiency of cargo-handling processes. At the same time, a significant proportion of port handling equipment, including equipment operated in Ukraine and other European countries, has exceeded or is approaching its original design service life. The replacement of such equipment requires substantial capital investment and may result in significant interruptions to port operations. Consequently, assessment of the possibility of safe and economically justified continued operation of aging equipment is an important engineering task.

Long-term operation under intensive cyclic loading, variable dynamic forces, and aggressive marine environmental conditions leads to the accumulation of several degradation mechanisms. These include fatigue damage of welded joints and structural members, corrosion-induced reduction of cross-sectional dimensions, permanent deformation, mechanical wear, and deterioration of lifting components. The simultaneous development of these mechanisms complicates the assessment of structural integrity because their effects may interact and accelerate the deterioration of critical components.

Conventional maintenance systems based mainly on scheduled inspections and predetermined maintenance intervals do not always reflect the actual technical condition of aging equipment. Two cranes of similar design and chronological age may have substantially different levels of degradation due to differences in loading history, operational intensity, environmental exposure, and maintenance quality. Therefore, chronological service life alone cannot be considered a sufficient criterion for determining the necessity and scope of maintenance interventions.

Contemporary maintenance engineering increasingly emphasizes condition-based and risk-informed approaches in which maintenance decisions are supported by objective information concerning the actual condition and operational duty of engineering assets. For cranes operating under long-term conditions, such information can be obtained through systematic inspections, non-destructive testing, monitoring of actual crane duty, structural analysis, and residual service-life assessment. ISO 12482:2014, for example, establishes a methodology for monitoring the actual duty of cranes during long-term operation and using this information to identify critical areas requiring additional inspection.

However, the practical integration of these approaches for aging port handling equipment remains insufficiently developed. In particular, there is a need for engineering procedures that connect the results of technical inspections with the assessment of structural integrity, residual service life, and maintenance decision-making. This issue is especially relevant to floating cranes and other port handling machines that have undergone long-term operation, repeated repairs, and modernization under marine environmental conditions.

Therefore, the development of an integrated engineering approach that combines technical inspection, degradation assessment, structural analysis, condition-based maintenance, and residual-life evaluation represents an important scientific and practical problem for ensuring the safe and economically justified operation of aging port handling equipment.

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

The technical condition and residual service life of aging lifting equipment have been investigated by numerous researchers due to the increasing number of cranes operating beyond their original design service life. Particular attention has been given to fatigue damage, corrosion degradation, structural integrity, residual life assessment, and the development of maintenance strategies based on the actual condition of engineering assets.

Fatigue remains one of the principal degradation mechanisms limiting the service life of crane steel structures. Long-term cyclic loading may lead to the initiation and propagation of cracks, particularly in welded joints, stress concentration zones, and highly loaded structural members. Methods based on fatigue damage accumulation, fracture mechanics, and crack-growth analysis are widely used to estimate the remaining fatigue life of crane structures [1, 2, 4]. These approaches make it possible to determine the relationship between the actual stress state of a structural element and its expected residual service life.

An additional degradation mechanism of particular importance for port handling equipment is corrosion. Marine atmospheric conditions characterized by high humidity, salt contamination, and cyclic wetting and drying accelerate corrosion of steel structures. Corrosion

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reduces the effective cross-sectional area of structural members and may simultaneously create local stress concentrations that facilitate fatigue crack initiation. Therefore, the combined effect of corrosion and cyclic loading should be considered when assessing the structural integrity of aging port cranes [3, 6, 7].

Several studies have demonstrated the applicability of engineering and numerical methods for assessing the condition of aging crane structures. Finite element analysis is widely used to determine stress and strain distributions, identify critical structural regions, and evaluate the influence of local defects on load-carrying capacity. When combined with information obtained from technical inspections, numerical modelling provides an additional basis for evaluating structural integrity and selecting appropriate repair or strengthening measures [5, 14].

The development of maintenance engineering has resulted in a transition from traditional time-based preventive maintenance toward Condition-Based Maintenance (CBM), Predictive Maintenance (PdM), and Risk-Based Maintenance (RBM). These approaches use information concerning the actual technical condition, operating history, loading intensity, and degradation rate of equipment to determine the appropriate timing and scope of maintenance interventions. For aging cranes, such approaches are particularly relevant because equipment of similar design and chronological age may have substantially different levels of deterioration.

International standards also increasingly emphasize the importance of condition assessment and monitoring during extended crane operation. ISO 9927-1 establishes general requirements for crane inspections, while ISO 12482 provides principles for monitoring the actual duty of cranes during their design working period and for identifying areas requiring additional inspection. The ISO 55000 series additionally considers asset management from a life-cycle perspective, linking technical condition, risk, maintenance planning, and economic considerations.

Recent research has expanded condition assessment through Structural Health Monitoring (SHM) systems based on strain, displacement, vibration, load, and other sensors. Continuous monitoring can provide information about the actual structural response under operating conditions and facilitate early identification of abnormal behaviour. Such systems are particularly promising for aging cranes because they can complement periodic inspections and provide additional information between scheduled examinations [8, 9].

Digital technologies, including Digital Twin models, have also been investigated as a means of integrating numerical structural models with real-time operational data. Such approaches can improve the estimation of actual loading, fatigue damage accumulation, and residual service life. However, their implementation for existing port handling equipment remains constrained by the availability of historical operational data, monitoring infrastructure, validated numerical models, and the economic feasibility of implementation [8, 9].

An important limitation of the existing research is that individual degradation mechanisms and maintenance technologies are frequently considered separately. Fatigue, corrosion, structural deformation, material degradation, non-destructive testing, numerical modelling, and condition-based maintenance are often investigated as independent components of the overall technical assessment. At the same time, the practical assessment of aging port handling equipment requires their integration because structural reliability is determined by the combined effect of material condition, accumulated loading, environmental exposure, existing defects, and future operating conditions.

This limitation is particularly relevant to floating cranes and other port handling machines that have been in service for several decades and may have undergone repeated repairs, replacement of individual components, or modernization. For such equipment, chronological service life cannot by itself provide a reliable indication of the actual technical condition or residual service life. Engineering decisions therefore require the integration of inspection results, material degradation indicators, structural analysis, operational history, and maintenance information.

The authors' previous investigations of port handling equipment have demonstrated the applicability of fractographic analysis, polarization resistance measurements, and structural stress analysis for evaluating degradation of crane materials and structural elements [12–14]. These results provide a basis for further development of an integrated approach in which material degradation indicators are considered together with structural condition and operational information.

Therefore, despite significant progress in fatigue assessment, corrosion monitoring, structural analysis, condition-based maintenance, and digital monitoring, there remains a need for an integrated engineering methodology specifically adapted to aging port handling equipment operating under long-term marine conditions. Such a methodology should connect the results of technical inspection and material diagnostics with structural integrity assessment, residual service-life evaluation, and maintenance decision-making. Addressing this gap constitutes the focus of the present study.

IDENTIFICATION OF PREVIOUSLY UNRESOLVED PARTS OF THE GENERAL PROBLEM

Despite significant progress in the development of methods for assessing the technical condition and residual service life of lifting equipment, the problem

of integrated assessment of aging port handling equipment remains insufficiently resolved. Existing studies predominantly focus on individual degradation mechanisms, such as fatigue damage, corrosion, structural deformation, or mechanical wear, or on individual diagnostic and maintenance technologies, including non-destructive testing, finite element analysis, Structural Health Monitoring, and Predictive Maintenance.

For port handling equipment operating under long-term marine conditions, however, these factors cannot be considered independently. The actual technical condition of a crane is determined by the combined influence of accumulated operating duty, cyclic loading, environmental exposure, material degradation, structural defects, and the effectiveness of previous maintenance and repair measures. The interaction of these factors may significantly affect the load-carrying capacity and residual service life of structural and mechanical components.

A further unresolved issue is the practical integration of material degradation assessment with structural condition assessment and maintenance decision-making. Information obtained during technical inspections is often used to identify individual defects, while the relationship between material degradation, structural integrity, operational loading, and residual service life remains insufficiently formalized. This limits the ability to make technically and economically justified decisions concerning continued operation, repair, strengthening, modernization, or replacement of aging equipment.

This problem is particularly important for floating cranes and other port handling machines that have operated for several decades and may have undergone repeated repairs and modernization. For such equipment, chronological service life is not a sufficient indicator of actual technical condition. A reliable assessment should account for both the present state of the material and structural elements and the accumulated operating history of the equipment.

Therefore, the unresolved scientific and engineering problem consists in developing an integrated approach that connects technical inspection, material degradation assessment, structural integrity evaluation, operational duty monitoring, residual service-life assessment, and condition-based maintenance into a unified decision-making framework for aging port handling equipment.

The solution to this problem would provide a more objective basis for determining the permissible further operation of aging cranes and for selecting appropriate maintenance interventions while balancing structural safety, operational reliability, and economic feasibility.

PURPOSE OF THE STUDY

The purpose of this study is to develop an integrated engineering approach for assessing the technical condition and residual service life of aging port handling equipment operating under long-term marine conditions. The approach combines technical inspection, assessment of material and structural degradation, structural integrity analysis, and condition-based maintenance principles to support justified decisions on continued operation, repair, modernization, or service-life extension of port cranes.

METHODS, OBJECT AND SUBJECT OF THE STUDY

The object of the study is aging floating cranes and other port handling equipment operating under long-term marine conditions. The subject of the study is the assessment of their technical condition and residual service life for substantiating maintenance and service-life extension decisions.

The study is based on technical inspection of crane structures and components, analysis of corrosion damage, fatigue cracks, permanent deformation and mechanical wear, assessment of material degradation, and structural stress–strain analysis. The research also considers the accumulated operating duty and the influence of long-term marine exposure on the degradation of crane structures.

The obtained results are used to identify critical degradation mechanisms and assess their influence on structural integrity and residual service life. The assessment results provide a basis for decisions concerning continued operation, repair, strengthening, modernization, or service-life extension of aging port handling equipment.

MAIN MATERIAL

The technical condition of port handling equipment operating beyond its design service life is determined by the combined influence of cyclic loading, marine environmental exposure, operational intensity, and previous maintenance. During long-term operation, several degradation mechanisms may develop simultaneously, including fatigue damage of welded joints and structural members, corrosion of steel elements, permanent deformation, and wear of mechanical and lifting components. Their combined effect may reduce structural reliability and load-carrying capacity and therefore requires an assessment based on the actual technical condition of the equipment [1–3].

Technical surveys of floating cranes operating under marine conditions showed that cranes of similar design and age may have significantly different levels of deterioration. The observed condition is associated not only with accumulated operating time but also with loading history, intensity of cargo-handling operations, environmental exposure, and the quality of previous maintenance and repairs. Therefore, chronological service life alone cannot be considered a sufficient criterion for assessing the possibility of further safe operation [4, 5].

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Steel wire ropes were among the critical components examined during technical inspections. Their condition is affected by repeated tensile loading, bending over sheaves, abrasive wear, and corrosion. Local defects and broken wires may reduce the load-carrying capacity of a rope and require timely replacement. The inspection of wire ropes therefore forms an important part of the overall assessment of crane safety [9] (Fig. 1).



Fig. 1. Floating crane operating under long-term marine service conditions

The inspection of crane steel structures revealed local permanent deformations of boom members and supporting structural elements (Fig. 2). Such deformation may result from excessive or repeated loading and can alter the geometry and stress distribution of the structure. In highly loaded regions, changes in stress distribution may contribute to the initiation and development of fatigue damage [1, 2, 14]. Consequently, detected deformation should be considered as a diagnostic indication requiring further assessment of the affected structural element.



Fig. 2. Replacement of worn steel wire ropes during maintenance

Corrosion was identified as another significant degradation mechanism affecting crane steel structures. Prolonged exposure to humid and saline marine environments promotes both general surface corrosion and localized corrosion near welded joints, stiffeners, drainage areas, and damaged protective coatings [3, 6, 7]. Reduction of the effective cross-sectional area and formation of local stress concentrations may decrease structural resistance and increase the susceptibility of steel elements to fatigue damage [6, 7]. Therefore, corrosion assessment should be considered together with the evaluation of the structural condition).

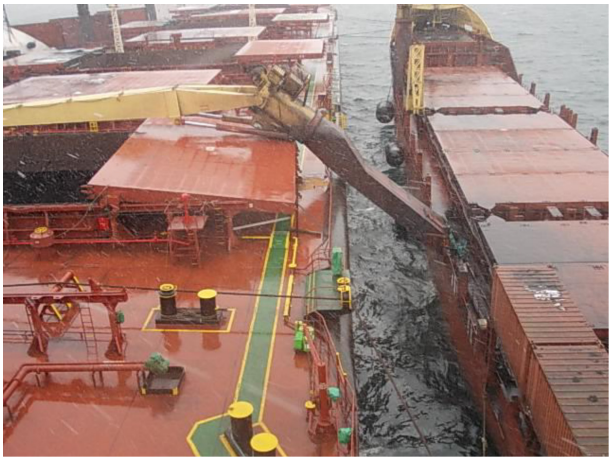


Fig. 3. Typical corrosion damage observed on crane structural elements

The inspection results also demonstrate the limitations of visual examination as the sole method of technical assessment. Visual inspection allows the identification of visible corrosion, deformation, cracks, and mechanical wear; however, defects may also develop in welded joints, connections, and other areas that are not accessible for direct visual examination. General requirements for crane inspections are established by ISO 9927-1:2013, which provides a framework for systematic inspection of crane components and structures [9]. Therefore, assessment of critical components should be supplemented, where required, by appropriate non-destructive testing and dimensional measurements.

The structural condition of aging cranes should additionally be assessed with regard to their accumulated operating duty and expected future loading. Structural analysis can be used to identify highly loaded regions and evaluate the influence of detected defects on the stress–strain state and load-carrying capacity. Finite element analysis and engineering assessment of crane structures can provide a basis for identifying critical regions and evaluating the remaining structural capacity [5, 14]. The combination of inspection data and structural analysis therefore supports decisions concerning continued operation, local repair, strengthening, modernization, or replacement of individual components.

For long-term crane operation, monitoring of the actual operating duty is also important. ISO 12482:2014

Table 1. Typical defects identified during technical inspections of aging port handling equipment and recommended engineering actions

Structural component	Typical deterioration mechanisms	Engineering implications	Recommended maintenance actions
Boom and supporting members	Permanent deformation, corrosion, fatigue cracks	Change in geometry and stress distribution; reduction of structural reliability	Detailed inspection, structural analysis, repair or strengthening [2, 14]
Welded joints	Fatigue cracks, corrosion	Local reduction of structural integrity and crack propagation risk	Non-destructive testing, repair of defective joints [2, 5]
Steel plates and structural elements	General and localized corrosion 20 %	Reduction of effective cross-sectional area	Thickness measurement, repair or replacement [3, 6, 7]
Steel wire ropes	Broken wires, wear, corrosion	Reduction of tensile and load-carrying capacity	Inspection and timely replacement [9]
Mechanical assemblies	Wear, corrosion, loss of dimensional accuracy	Increased loads, reduced operational reliability	Adjustment, repair or replacement

provides principles for monitoring crane duty during operation and using information on the actual loading history to identify critical areas requiring additional inspection [10]. This approach is particularly relevant to aging equipment because the actual operating conditions may differ substantially from the assumptions used during the original design.

The identified degradation mechanisms and their engineering consequences are summarized in Table 1.

The results presented above indicate that the assessment of aging port handling equipment should combine the identification of individual defects with an evaluation of their influence on the overall structural condition. The integration of technical inspection, structural analysis, and monitoring of actual crane duty provides a more reliable basis for assessing the condition of aging equipment and planning further maintenance interventions [10, 14].

The application of condition-based maintenance principles is particularly relevant in this context. Unlike maintenance based exclusively on predetermined intervals, Condition-Based Maintenance uses information on the actual condition of equipment to determine the timing and scope of maintenance interventions. Such an approach is consistent with the principles of systematic asset management and condition-oriented maintenance planning [10, 15].

The assessment of aging crane structures should therefore consider not only visible defects but also the degradation of the material itself. Previous studies by the author demonstrated the applicability of fractographic analysis for assessing the loss of resistance to brittle fracture in steels used in cargo-handling equipment [12] and the use of polarization resistance measurements for monitoring degradation of steels in port crane structures [13]. These results provide an additional basis for integrating material condition indicators into the overall technical condition assessment of aging port handling equipment.

DISCUSSION OF THE OBTAINED RESULTS

The obtained results indicate that the technical condition of aging port handling equipment is determined by the combined action of fatigue loading, corrosion, permanent deformation, and mechanical wear. The simultaneous development of these degradation mechanisms complicates the assessment of structural reliability and confirms the need to evaluate the actual technical condition rather than rely solely on the chronological service life of the equipment [1–4].

The interaction between corrosion and fatigue is particularly important for cranes operating in marine environments. Corrosion reduces the effective cross-sectional area of structural members and creates local stress concentrations, while cyclic loading contributes to fatigue crack initiation and propagation in weakened areas. Previous studies have demonstrated the influence of corrosion on the fatigue behaviour of aged crane steels and the significance of corrosion-fatigue degradation in marine crane structures [6, 7]. These findings are consistent with the engineering observations obtained during the technical inspections considered in this study.

Permanent deformation of boom and supporting structural elements should also be regarded as an important diagnostic indicator. Such deformation may result from excessive loading, local yielding, or long-term accumulation of structural damage and can alter the distribution of internal forces within the structure. Therefore, detected deformation requires additional engineering assessment rather than being considered only as a geometric deviation.

The results further confirm that visual inspection alone is insufficient for reliable assessment of critical crane components. Hidden defects in welded joints and highly loaded structural elements require additional diagnostic procedures, including appropriate non-destructive testing and dimensional measurements. The combination of inspection data with engineering calculations and structural analysis provides a more reliable basis for evaluating the consequences of detected defects and the residual load-carrying capacity of the structure [4, 5, 14].

The analysis supports the application of Condition-Based Maintenance (CBM) to aging port handling

equipment. The actual condition of cranes of similar age may differ considerably because of differences in loading history, operating intensity, environmental exposure, and previous maintenance. Consequently, maintenance decisions should be based on the measured condition and accumulated operational duty of individual components. This principle corresponds to the life-cycle and risk-oriented asset-management approach established by ISO 55000:2024 [5].

Monitoring of actual crane duty is particularly relevant for equipment operating for extended periods. ISO 12482:2014 provides a methodology for monitoring the actual duty of cranes and comparing it with the original design duty, thereby supporting the identification of critical areas requiring additional inspection [10]. Thus, operational-duty monitoring can complement periodic technical inspections and improve the substantiation of maintenance decisions.

Structural analysis, including finite element modelling, provides an additional means of identifying highly stressed regions and assessing the influence of detected defects on structural behaviour. The combination of inspection data with stress–strain analysis and fatigue assessment can support decisions concerning continued operation, repair, strengthening, modernization, or service-life extension [4, 5, 14].

Digital monitoring and Digital Twin technologies represent a further development of this approach. Numerical models combined with operational and monitoring data can improve the assessment of structural response and support fatigue-life prediction. The feasibility of digital-twin-based monitoring of crane structures has been demonstrated in recent research [8]. However, for existing port equipment, implementation depends on the availability of monitoring systems, reliable operational data, suitable numerical models, and economically justified implementation costs.

From a practical engineering perspective, the obtained results demonstrate that the presence of a defect does not necessarily require replacement of the entire crane. Depending on its location, severity, influence on structural integrity, and expected operating conditions, appropriate measures may include local repair, replacement of individual components, structural strengthening, increased inspection frequency, installation of monitoring equipment, or controlled continued operation. Such differentiation provides a technical basis for economically justified service-life extension while maintaining the required level of safety.

Overall, the results substantiate an integrated approach combining technical inspection, non-destructive testing, structural analysis, monitoring of actual crane duty, residual-life assessment, and condition-based maintenance. The proposed approach is particularly applicable to aging floating cranes operating under long-term marine conditions and provides a more informative basis for maintenance planning than scheduled inspections considered independently.

CONCLUSIONS

The study demonstrates that the technical condition of aging port handling equipment is determined by the combined influence of fatigue loading, corrosion, permanent deformation, and mechanical wear. Their simultaneous development reduces structural reliability and requires an integrated assessment of the actual technical condition of cranes.

The engineering observations confirm that visual inspection alone is insufficient for assessing critical structural and mechanical components. The use of non-destructive testing, dimensional measurements, structural analysis, and monitoring of actual operating conditions provides a more reliable basis for evaluating structural integrity and residual service life.

The results show that corrosion and fatigue should be considered as interrelated degradation mechanisms, particularly for crane structures operating in marine environments. Their combined influence can accelerate deterioration of structural elements and therefore should be considered when determining the need for repair, strengthening, or further inspection [3, 6, 7].

The study substantiates the applicability of Condition-Based Maintenance for aging port handling equipment. Maintenance decisions should be based on the actual technical condition, accumulated operational duty, and severity of detected defects rather than on chronological service life alone. Monitoring of actual crane duty in accordance with ISO 12482:2014 can provide additional information for identifying components requiring detailed inspection [10].

The integration of inspection results with structural analysis and residual-life assessment provides an engineering basis for selecting appropriate maintenance measures, including continued controlled operation, increased inspection frequency, repair, replacement of individual components, structural strengthening, modernization, or service-life extension [4, 5, 14].

Digital monitoring and Digital Twin technologies can further improve condition assessment and residual-life prediction by combining numerical models with operational data. However, their implementation for existing port equipment should be based on the availability of monitoring data, appropriate numerical models, and economic feasibility [8].

Thus, the main result of the study is the substantiation of an integrated maintenance framework combining technical inspection, non-destructive testing, structural assessment, monitoring of actual crane duty, residual-life evaluation, and Condition-Based Maintenance. The proposed approach provides a methodological basis for safer and economically justified extension of the service

life of aging port handling equipment operating under long-term marine conditions.

Під час підготовки статті використовувалися інструменти штучного інтелекту для мовного редагування, перевірки граматики, стилістичного вдосконалення та перекладу окремих фрагментів тексту. Зміст, наукові положення, результати дослідження та висновки сформовані авторами, які несуть відповідальність за достовірність і коректність представленої інформації.

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