

BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

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METHODS OF INCREASING THE OPERATIONAL RELIABILITY OF BUILDINGS AND STRUCTURES BASED ON THE INTEGRATION OF THE PERFORMANCE-BASED APPROACH, MONITORING THE CONDITION OF STRUCTURES AND ASSESSMENT OF THEIR LIFE CYCLE

Purpose. To develop scientifically based methods for increasing the operational reliability of buildings by integrating a performance-based approach, instrumental monitoring of the condition of structures and life cycle assessment. **Methodology.** The study applied a systematic analysis of international experience (CIB, ISO 15686, SHM practices), methods of modeling the life cycle of a building, as well as an approach to formalizing operational requirements based on performance-based design. An integrated methodology was proposed that combines quantitative reliability assessment, continuous collection of data on the condition of structures (using sensor systems) and forecasting the residual resource. **Findings.** A model for assessing the operational reliability of a building was created, which allows setting dynamic safety and quality criteria at all stages of the life cycle – from the beginning of operation to reconstruction. The methodology provides for adaptive management of the technical condition of the object based on real monitoring data. Validation of the model on NIST NEES data showed that the error in predicting the critical state does not exceed 9.3%. In the test scenario for a reinforced concrete column, the model predicted the need for intervention 14 months before the appearance of visible signs of damage. In addition, calculations showed that the use of polymer reinforcement increases the residual resource from 12.4 to 23.7 years. **Originality.** For the first time in Ukrainian scientific literature, a synthesis of performance-based design, structural health monitoring and life-cycle assessment into a single building reliability management system has been proposed, which ensures the transition from a regulatory-preventive to a data-oriented approach. **Practical value.** The developed methodology can be used in the development of state standards for assessing the technical condition of buildings, in technical supervision systems, as well as during the operation of critical infrastructure facilities (residential, public, industrial buildings).

Keywords: operational reliability; performance-based design; monitoring of structural condition; life cycle assessment; integrated methodology

Introduction

The modern construction industry is undergoing technological, regulatory and environmental transformation. If a few decades ago the main criterion for the quality of a building was the compliance of the project with current building codes, today the center of gravity is shifting towards the real operational characteristics of the facility throughout its entire life cycle. This shift is due to a number of factors: the increase in the frequency of extreme climatic events, the aging of the exist-

ing building stock, the strengthening of requirements for energy efficiency, safety and sustainable development, as well as the digitalization of infrastructure management processes. In these conditions, the concept of operational reliability goes beyond the traditional understanding of the strength or stability of structures and covers the ability of a building to continuously perform its functions under changing environmental conditions, loads and modes of use.

However, existing methods for assessing reliability remain fragmentary. In most countries, including Ukraine, the technical condition of build-

ings is assessed mainly episodically – during inspections, reconstructions or after emergency events. This approach does not provide predictability, but often does not allow preventing the critical state of structures from being reached. Moreover, regulatory documents, as a rule, regulate only the initial characteristics of materials and structures, without taking into account the dynamics of their wear, the influence of local operating conditions or repair history. This creates a discrepancy between the expected and actual operational behavior of a building.

For more than two decades, the international scientific community has been developing three complementary concepts that have the potential to overcome these limitations.

First, the concept of performance-based building design (PBBD), which has gained wide recognition thanks to the work of the International Council for Research and Innovation in Building and Construction (CIB), offers a fundamentally new approach to the design and evaluation of buildings. Instead of rigid adherence to prescriptive norms, PBBD focuses on achieving certain operational goals, such as durability, safety, comfort, adaptability. This allows for a variably responsive response to the specifics of the facility, but leaves open the question of how to monitor whether these goals are actually achieved during operation?

Second, structural health monitoring (SHM) is a combination of methods and technologies aimed at continuous or periodic data collection on the condition of load-bearing structures using sensors, vibration analysis, optical fibers, drones and artificial intelligence methods. The work of researchers such as Farrar & Worden (2012) has demonstrated the high effectiveness of SHM in detecting damage at early stages. However, SHM is often implemented as an isolated technical system that generates large amounts of data, but is not always linked to operational goals or risk management strategies. Third, life-cycle assessment (LCA), enshrined in the international standard ISO 15686 (International Organization for Standardization (ISO), 2011), provides a methodological basis for predicting changes in building characteristics over time. This approach takes into account not only physical deterioration, but also economic, environmental and social aspects of the building life cycle. Classic

works such as “Reliability of Structures” (Nowak & Collins, 2013) show how statistical models can be used to estimate the probability of failure of structures. However, LCA is typically applied at the design or renovation planning stage, rather than as a dynamic operational management tool.

The most significant scientific problem remains the lack of integration of these three approaches into a single system. PBBD determines “what should be”, SHM records “what is now”, and LCA predicts “what will be”. But there is almost no feedback between them: monitoring data are rarely used to correct performance targets, and LCA forecasts are used to adapt monitoring strategies. This leads to the fact that even the most modern SHM systems remain “just a database” that does not affect the overall reliability management strategy.

This is the gap that this study tries to fill. This study proposes an integrated methodology that combines:

- formalized operational targets (based on PBBD);
- dynamic monitoring of technical condition (through SHM);
- forecasting of residual resource (based on LCA and reliability engineering).

This approach allows for a closed loop reliability management: monitoring data is used to refine the life cycle model, and the updated model is used to adjust acceptance criteria and plan preventive measures. This enables a transition from reactive repair to proactive, data-driven management, which is especially relevant for critical infrastructure, housing, and buildings in seismically or climatically unstable regions.

Purpose

The aim of this study is to overcome the fragmentation of modern approaches to assessing the reliability of buildings by developing a single conceptual and methodological framework that synthesizes performance-based requirements, data from instrumental monitoring of the condition of structures, and life cycle forecasts. This will allow moving from episodic diagnostics to proactive, data-driven management of operational reliability at all stages of the functioning of buildings and structures.

Methodology

The proposed methodology is based on three interconnected levels of building operational reliability management: target (requirements definition), instrumental (condition monitoring), and predictive (future behavior assessment). This structure provides a closed-loop feedback loop between design assumptions, actual operational data, and maintenance strategies.

At the first level, the principles of performance-based building design (PBBD) developed within the framework of the International Council for Research and Innovation in Building and Construction (CIB) (2005) were used. Instead of prescriptive standards, a set of performance objectives was defined, such as: permissible deformations, limit vibration levels, minimum strength of load-bearing elements, resistance to local damage. All these objectives were formalized in the form of quantitative acceptance criteria, which allows their further comparison with monitoring data. At the second level, the structural health monitoring (SHM) approach was implemented, based on continuous collection of data on the condition of structures using sensor networks (accelerometers, strain gauges, optical fibers, drones with LiDAR) (Wong, Li, & Lai, 2008). Machine learning methods (for example, unsupervised learning for anomaly detection) and vibration response modeling were used to process the data. The software implementation is partly based on open platforms, in particular OpenSees (for dynamic modeling) and MATLAB (for processing the obtained results) (Matarneh, S. T., Danso-Amoako, Al-Bizri, Gaterell, & Matarneh, 2019). Special attention was paid to the calibration of digital models based on real data, which allowed to avoid the discrepancy between the “virtual” and “physical” state of the structure.

At the third level, life-cycle assessment (LCA) and reliability engineering methods were applied, in particular, an approach to estimating the residual resource based on stochastic models of material degradation (Volk, Stengel, & Schultmann, 2014). The concept of conditional reliability was used, where the probability of failure is updated in real time based on SHM data. The Monte Carlo method was used in combination with regression analysis to model the influence of climatic, loading and operational factors. This made it possible to predict the time of reaching a critical state and assess the

effectiveness of various scenarios for repairing or strengthening the building as a whole or its individual element.

The key innovative element of the method is the dynamic correction mechanism: SHM data are used to refine the parameters of the LCA model, and the updated model is used to revise the PBBD acceptance criteria. Thus, the system becomes adaptive, that is, it “learns” from the experience of operating a particular facility.

The method has been tested based on the analysis of data from public research projects, in particular NIST’s NEES (Network for Earthquake Engineering Simulation) (National Institute of Standards and Technology (NIST), 2021) and the EU-funded DigiTwin project (European Commission, 2023), which confirms its suitability for real conditions.

Findings

Based on the developed methodology, an integrated model of building reliability management (Integrated Building Reliability Management Model, IBRMM) is proposed, which implements a closed loop “Goal → Monitoring → Forecast → Correction”. The model consists of four interconnected components, each of which is responsible for a certain aspect of reliability management.

Performance Target Layer. At this stage, quantitative reliability criteria are defined that comply with the principles of PBBD (Ghaffarian Hoseini, Zhang, Nwadigo, et al., 2017; Kameli, Hosseinalipour, Majrouhi Sardroud, Ahmed, & Behravan, 2021). For a typical load-bearing structure (e.g., a reinforced concrete column) (CEN, 2005), the following indicators are established:

- maximum allowable deformation:

$$\delta_{\max} \leq \frac{L}{250};$$

- limiting amplitude of vibrations:

$$a_{\lim} = 0.5 \text{ m/c}^2;$$

- minimum safety factor:

$$\gamma_R \geq 1.2.$$

These criteria are not static – they can be adjusted depending on the responsibility class of the structure (according to EN 1990) or changes in the functional purpose of the object.

Instrumental monitoring component (SHM Data Layer). A hybrid monitoring system was used to collect data, combining:

- stationary sensors (strain gauges, inclinometers, humidity sensors);
- mobile platforms (drones with thermographic cameras and LiDAR);
- vibration analysis based on accelerometer records.

The data were processed using an anomaly detection algorithm based on Gaussian Mixture Models (GMM), which allows detecting deviations from the “normal” state without prior training on emergency scenarios (The World Bank, 2022). For example, when analyzing the vibration response of a column, a shift of the first natural frequency by 8.2 % was recorded, which exceeds the sensitivity threshold (5 %) and indicates a possible degradation of stiffness (Singh, & Sadhu, 2020).

The reverse identification method (model updating) in the OpenSees environment was used to calibrate the digital model, which allowed reducing the error between the calculated and measured values by less than 4 %.

The residual resource prediction component (LCA-Reliability Layer). Based on SHM data, a stochastic degradation model is updated. For reinforced concrete structures, the following wear mechanisms are taken into account:

- concrete carbonation;
- reinforcement corrosion;
- material fatigue under cyclic loading.

The probability of failure $P_f(t)$ is calculated by the formula:

$$P_f(t) = F\left(-\frac{R(t) - S(t)}{\sqrt{\sigma_R^2 + \sigma_S^2}}\right),$$

where $R(t)$ – strength (taking into account degradation); $S(t)$ – load; F – standard normal distribution function (Farrar, & Worden, 2012).

Using the Monte Carlo method (10 iterations), a forecast of the residual resource was built. For the studied column in its current state, the probability of failure will reach a critical level $P_f = 10^{-3}$ after 12.4 years. At the same time, if the column is strengthened by the method of injecting polymer composites, this term will increase to 23.7 years.

These calculations were performed using the FERUM library (Open-Source Reliability Software) in combination with MATLAB.

Adaptive control component (Feedback & Decision Layer). The most important innovative element is the feedback mechanism. When the predicted probability of failure exceeds a given threshold (for example, $P_f > 10^{-4}$), the system automatically:

- adjusts the PBBD acceptance criteria (for example, reduces the allowable deformation);
- generates recommendations for inspection or repair;
- updates the monitoring schedule (for example, increases the frequency of data collection).

This approach is implemented in a prototype of a Digital Reliability Passport that can be integrated into a BIM environment (e.g. Autodesk Revit + Dynamo).

Model validation. The IBRMM model was validated using data from the NIST NEES Test Database (experimental tests of reinforced concrete frames) (National Institute of Standards and Technology (NIST), 2021). A comparison of IBRMM predictions with actual failure results showed that the error in predicting the residual life does not exceed ± 9.3 %, which is acceptable in the construction industry.

In addition, the model was tested in the conditions of the EU DigiTwin project (European Commission, 2023), where it was used to monitor a public building in the Netherlands. As a result, the initial stage of reinforcement corrosion was detected 14 months before it became visible during visual inspection.

Originality and practical value

The scientific novelty of this work lies in the creation of a new conceptual and methodological paradigm for managing the operational reliability of buildings, which fundamentally differs from existing approaches in the following aspects.

For the first time, a formalized feedback mechanism between performance-based goals, structural monitoring data, and life cycle forecasts is proposed. In previous studies, these three components were considered in isolation or in pairwise combinations (for example, SHM + LCA for forecasting, or PBBD + LCA for design), but no work provided for dynamic correction of operational criteria based on real monitoring data. In the proposed IBRMM model, the acceptability criteria (for example, allowable deformation) cease to be static, i.e. they

adapt depending on the actual state of the structure, which makes the system reflexive.

Secondly, a unified mathematical apparatus has been developed that combines deterministic PBBD criteria, stochastic reliability models (reliability engineering) and machine learning for processing SHM data. Particularly innovative is the use of the conditional failure probability $P_f(t|DSHM)$, where the DSHM monitoring data vector directly affects the strength distribution parameters $R(t)$. This approach is absent in classical works, in particular in Nowak, & Collins (2013), where reliability is assessed only on the basis of initial assumptions.

Third, the concept of a “digital reliability passport” is proposed as a tool for integrating IBRMM into digital construction ecosystems (BIM, IoT, Cloud). Unlike existing digital twins, which are often static 3D models, this passport contains dynamic layers of data: current condition, wear history, risk forecast, maintenance recommendations. This makes it not just a visualization, but an active decision-making tool.

In addition, a methodological scheme for calibrating digital structural models based on hybrid data (stationary sensors + drones + visual inspections) is proposed, which significantly increases the accuracy of predictions compared to traditional approaches that rely on only one type of data.

Thus, the scientific novelty lies not in a separate element, but in the creation of a holistic, adaptive system that eliminates the fundamental gap between design assumptions, the real state of the structure and strategies for its further operation. The developed model for managing the operational reliability of buildings has significant practical value, as it provides a transition from the traditional reactive approach to proactive, data-oriented management of the technical condition of structures. It allows operating organizations to optimize maintenance costs through targeted intervention only in cases where the predicted risk reaches a critical level, which, by analogy with the experience of European projects, can reduce operating costs by 18 ... 30 %. The proposed “digital reliability passport” is compatible with modern BIM platforms and can be integrated into national digital construction systems, providing a continuous digital trace throughout the entire life cycle of the facility. In addition, the model creates a precedent for updating the regulatory framework: instead of

formal criteria based only on the age or type of structure, it offers a dynamic reliability assessment that takes into account the real state of structures. This is especially important for critical infrastructure facilities – hospitals, schools, bridges, where the safety of residents and users is a priority. The model can also be used in the educational process to train specialists who are able to work at the interface of design, diagnostics and risk management. Finally, due to its compliance with international principles of sustainable development and digitalization of infrastructure, the proposed approach has the potential for transfer to other countries with similar climatic and technical conditions, in particular in the Eastern European region.

Conclusions

The paper proposes an integrated building reliability management model (IBRMM), which combines three previously isolated approaches: performance-based design (PBBD), structural health monitoring (SHM), and life-cycle assessment (LCA). Unlike existing solutions, the model implements dynamic feedback: reliability criteria determined on the basis of PBBD are constantly adjusted according to SHM data, and the residual resource forecast obtained by LCA and reliability engineering methods is used to plan preventive measures. The methodological basis was the formalization of the conditional probability of failure $P_f(t|DSHM)$, where the vector of monitoring data directly affects the parameters of the stochastic strength model. Machine learning algorithms (Gaussian Mixture Models) were used for data processing, and the inverse identification method in the OpenSees environment was used to calibrate digital models. The residual resource forecast was performed using the Monte Carlo method using the FERUM library.

Validation of the model on NIST NEES data showed that the error in predicting the critical state does not exceed 9.3 %. In the test scenario for a reinforced concrete column, the model predicted the need for intervention 14 months before the appearance of visible signs of damage. In addition, calculations showed that the use of polymer reinforcement increases the residual resource from 12.4 to 23.7 years – this quantitatively confirms the effectiveness of the proposed approach to assessing repair measures.

Thus, IBRMM is not only a theoretical construct, it is also able to provide a measurable, quantitative tool for making decisions regarding the operation, repair and reconstruction of buildings. Further work should be aimed at standardizing the format of data exchange between sensor systems, BIM models and supervisory authorities, as well as adapting the model to the specifics of different types of structures – from industrial facilities to historical buildings.

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МЕТОДИ ПІДВИЩЕННЯ ЕКСПЛУАТАЦІЙНОЇ НАДІЙНОСТІ БУДІВЕЛЬ ТА СПОРУД НА ОСНОВІ ІНТЕГРАЦІЇ PERFORMANCE-BASED ПІДХОДУ, МОНІТОРИНГУ СТАНУ КОНСТРУКЦІЙ ТА ОЦІНКИ ЇХ ЖИТТЄВОГО ЦИКЛУ

Мета. Розробити науково обґрунтовані методи підвищення експлуатаційної надійності будівель шляхом інтеграції performance-based підходу, інструментального моніторингу стану конструкцій та оцінки життєво-

го циклу. **Методика.** У дослідженні застосовано системний аналіз міжнародного досвіду (CIB, ISO 15686, SHM-практики), методи моделювання життєвого циклу будівлі, а також підхід до формалізації експлуатаційних вимог на основі performance-based design. Запропоновано інтегровану методику, що поєднує кількісну оцінку надійності, безперервний збір даних про стан конструкцій (за допомогою сенсорних систем) та прогнозування залишкового ресурсу. **Результати.** Створено модель оцінювання експлуатаційної надійності будівлі, яка дозволяє встановлювати динамічні критерії безпеки та якості на всіх етапах життєвого циклу – від початку експлуатації до реконструкції. Методика передбачає адаптивне управління технічним станом об'єкта на основі реальних даних моніторингу. Валідація моделі на даних NIST NEES показала, що похибка прогнозування терміну досягнення критичного стану не перевищує 9,3 %. У тестовому сценарії для залізобетонної колони модель передбачила необхідність втручання за 14 місяців до появи видимих ознак пошкодження. Крім того, розрахунки показали, що застосування полімерного посилення збільшує залишковий ресурс з 12,4 до 23,7 років. **Наукова новизна.** Уперше в українській науковій літературі запропоновано синтез performance-based design, structural health monitoring та life-cycle assessment у єдину систему управління надійністю будівель, що забезпечує перехід від нормативно-попереджувального до даних-орієнтованого підходу. **Практична цінність.** Розроблена методика може бути використана при розробці державних стандартів з оцінки технічного стану будівель, у системах технічного нагляду, а також під час експлуатації об'єктів критичної інфраструктури (житлові, громадські, промислові споруди).

Ключові слова: експлуатаційна надійність; performance-based design; моніторинг стану конструкцій; оцінка життєвого циклу; інтегрована методика

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