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MATHEMATICAL MODELING AND FORECASTING METHODS BASED ON SENSOR DATA FOR MONITORING THE TECHNICAL CONDITION OF BUILDINGS AND STRUCTURES

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Abstract

In recent years, the issue of reliable assessment of the technical condition of buildings and structures during operation has become one of the most pressing challenges. Traditional visual inspections and periodic surveys are insufficient for identifying structural changes that occur in real time. This article analyzes mathematical modeling and forecasting methods based on modern sensor systems for monitoring the technical condition of buildings and structures. In the study, deformation, stress, vibration, and deterioration processes are described using mathematical equations. The obtained results demonstrate that the proposed approach enables early assessment of the technical condition and timely detection of potentially hazardous states.

Keywords: technical condition monitoring, sensor systems, mathematical modeling, deformation, dynamic analysis, forecasting.

Introduction

The acceleration of urbanization processes, the extension of the service life of buildings and structures, and the increasing magnitude of applied loads

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necessitate continuous monitoring of their technical condition. This is particularly important for buildings located in seismically active regions, where timely assessment of the condition of structural elements is of critical significance. Existing technical inspection methods are mainly based on periodic and visual assessments, which do not allow the detection of deformation and dynamic changes occurring in real time. Therefore, in recent years, monitoring approaches based on sensor technologies, IoT platforms, BIM, and Digital Twin systems have been widely implemented. The main objective of this study is to develop mathematical models based on sensor data for monitoring the technical condition of buildings and structures and to scientifically substantiate their forecasting capabilities.

Research Methods

Monitoring System Structure

The monitoring system designed to assess the technical condition of buildings and structures is intended for continuous observation of mechanical and physical processes occurring in structural elements and consists of several functional levels. The main purpose of the monitoring system is to identify the response of structural elements to deformation, vibration, and environmental influences, as well as to collect these data for subsequent mathematical analysis.

In this study, the methodology is based on the use of the following types of sensors:

- Deformation sensors (strain gauges) are used to measure relative elongation or contraction occurring in structural elements. These sensors are installed at critical sections of columns and beams where maximum stress is expected, enabling the monitoring of deviations of the material behavior from the elastic state.
- **Vibration and acceleration sensors (accelerometers)** are used to determine the vibration frequency, amplitude, and acceleration of structures under dynamic loading conditions. These data are of great importance for assessing the dynamic

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characteristics of a building, particularly its natural frequencies and proximity to resonance conditions.

- **Temperature and humidity sensors** are used to account for environmental factors affecting the physico-mechanical properties of structural materials. Since changes in temperature and humidity can significantly influence deformation indicators, these parameters are mandatorily considered during the monitoring process.
- IoT-based data transmission modules ensure the real-time transfer of signals obtained from sensors to a central server or database. These modules enable continuous operation of the monitoring system and provide the capability for remote analysis.

All data received from the sensors are first subjected to filtering and normalization processes, and then prepared for subsequent mathematical and statistical analysis.

Object of the Study

The object of the study is the main structural elements of a multi-story public building that are subjected to the greatest loads during operation. These elements include:

- **Columns** that bear vertical loads;
- **Beams** that transfer horizontal and bending loads;
- **Enclosing and inter-floor structures** that ensure the spatial rigidity of the building.

The primary reason for selecting these structural elements for monitoring is their decisive role in the overall stability and safety of the building. During the study, deformations and dynamic changes occurring in these elements were considered as key indicators of the technical condition.

Research Methods

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During the study, a comprehensive approach was applied, utilizing several interrelated scientific methods aimed at assessing the technical condition of buildings and structures.

- Statistical analysis method was used to determine the distribution, average values, and maximum and minimum indicators of the data obtained from the sensors. This method allowed for assessing data stability and identifying random fluctuations.
- The mathematical modeling method was used to represent the deformation, stress, and deterioration processes of structural elements through analytical equations. This approach allows for comparison of real measurement results with the theoretical model.
- The dynamic analysis method is aimed at assessing the vibration state of the building, determining its natural frequencies, and identifying hazardous conditions arising under dynamic loads. This method allows for accounting for the effects of seismic and man-made loads.
- Regression and forecasting methods were used to predict the future technical condition based on deformation and vibration indicators changing over time. These methods serve to identify potentially hazardous conditions that may occur during the operation of structures in advance.

Results

Based on the data obtained from the monitoring system, the technical condition of the main structural elements of the building was assessed. Continuous measurements collected through sensors made it possible to identify the time-dependent changes in deformation and dynamic vibration processes. The results reflected how structural elements respond mechanically under real operational conditions.

Analysis of deformation sensor data showed that the relative deformations occurring in structural elements continuously change during operation and, in

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some cases, approach the limit values specified in current regulatory documents. This indicates the accumulation of stress in the structures and changes in material properties over time. Results from vibration and acceleration sensors allowed the determination of the building's dynamic characteristics. Changes in vibration frequency and amplitude of structural elements were observed under dynamic loads, including external mechanical impacts and operational vibrations. These changes reflect the building's stiffness characteristics and the evolution of its structural condition.

Long-term monitoring results enabled the identification of the gradual development of deterioration processes in structural elements. Deformation and vibration data analyzed together with temperature and humidity indicators showed a decrease in the physico-mechanical properties of materials over time. This process directly affects the technical condition of structures throughout their service life. The findings demonstrate that assessing the technical condition based solely on visual inspection is insufficient to detect hidden deformations and dynamic changes in structural elements. An approach based on sensor monitoring provides a more accurate evaluation of the actual condition of buildings and structures and plays a significant scientific and practical role in ensuring their operational safety [1-4].

Discussion

Mathematical Representation of Deformation. Deformation is one of the most important mechanical indicators for assessing the technical condition of structural elements. It represents the change in geometric dimensions of a structural element under external loads and is directly related to the material condition and the nature of the applied load.

The relative deformation describes the change in the length of a structural element over time and is defined by the following expression:

$$\varepsilon(t) = \frac{\Delta L(t)}{L_0}$$

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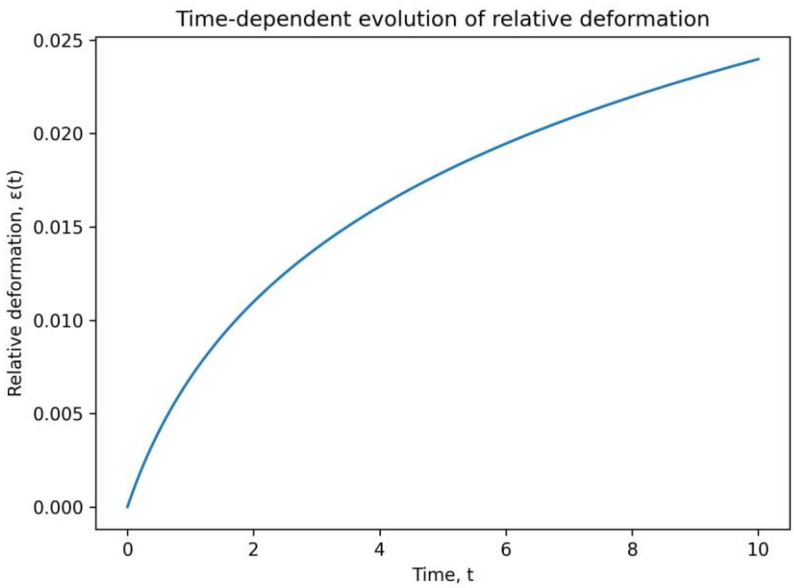
where:
$\Delta L(t)$ — is the change in length of the element at time t,
L_0 — is the original length of the element.



This mathematical expression allows for the physical interpretation of real measurement results obtained from deformation sensors. Analyzing deformation indicators over time is crucial for identifying the accumulation of stress in structural elements and for assessing trends in the deterioration of their technical condition.

Relationship Between Stress and Deformation. For structural materials in the elastic state, the relationship between stress and deformation is based on classical elasticity theory. This relationship is described by Hooke's law and can be expressed by the following equation:

$\sigma(t)=E \cdot \varepsilon(t)$

where:
$\sigma(t)$— is the stress in the material,
E — is the modulus of elasticity of the material,
$\varepsilon(t)$— is the corresponding strain.

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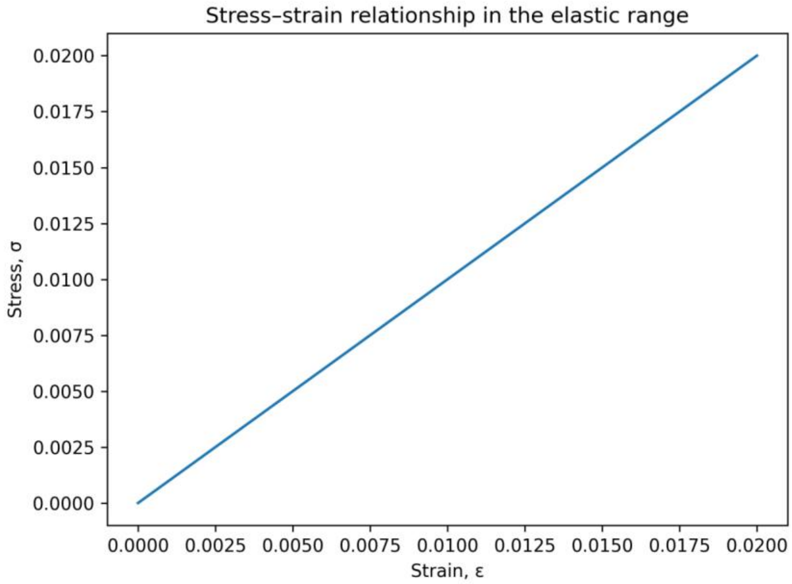

This relationship allows for the indirect determination of stresses occurring in structural elements based on deformation values measured by sensors. As a result, conditions approaching the elastic limit of the material can be identified, increasing the reliability of technical condition assessments. The stress–strain relationship serves as a fundamental theoretical basis for analyzing the safe operation of structures.

Dynamic Vibration Model. Buildings and structures are subjected to constant and variable dynamic loads during operation. These loads induce vibration processes in structural elements [5-8]. To mathematically represent the vibration state, the classical second-order differential equation is used:

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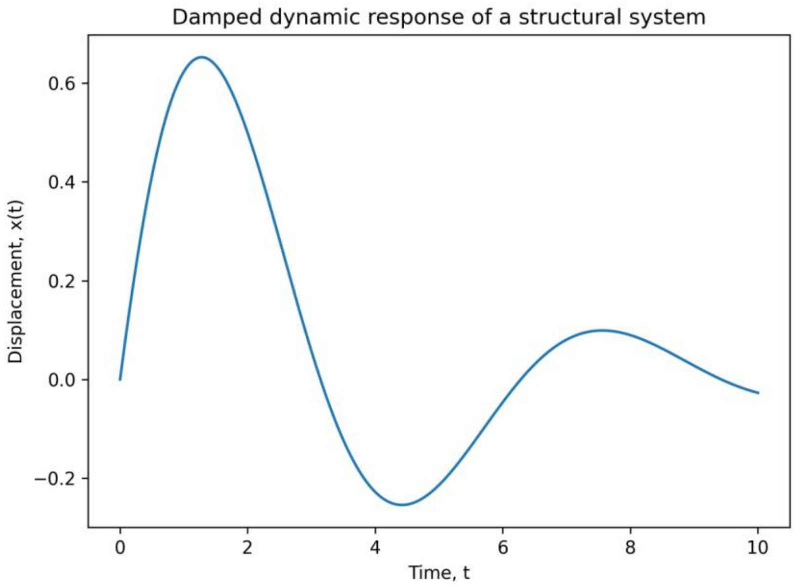

This model enables the analysis of the dynamic response of structural elements and the determination of the time-dependent variations of vibration amplitude and acceleration, and by comparing the vibration data obtained from monitoring systems with this mathematical model, conclusions can be drawn regarding the dynamic characteristics of the structures.

Natural frequency and resonance risk are considered, as each building or structural system has its own characteristic natural vibration frequency, which is determined by the mass and stiffness of the structure and can be expressed by the following formula.

$$\omega_0 = \sqrt{\frac{k}{m}}$$

The natural frequencies obtained from monitoring are compared with the actual vibration frequencies. If the vibration frequency detected during operation approaches the natural frequency, a resonance phenomenon may occur. Since resonance leads to a sharp increase in stresses within structural elements, this condition is given special attention in structural health monitoring [9-11].

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Wear (Degradation) Assessment Model. During long-term operation, the physical and mechanical properties of structural elements gradually change. This process is described by the concept of wear (degradation). To mathematically evaluate the wear process, an exponential model is employed:

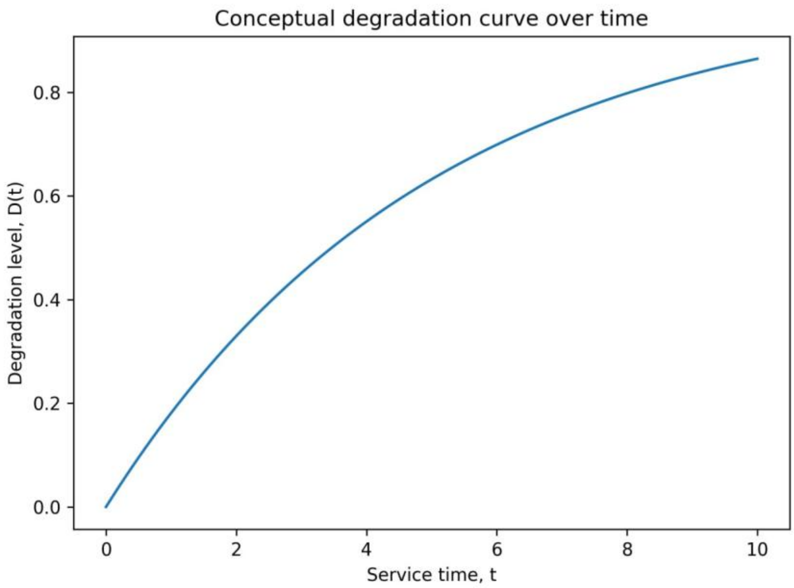
$D(t) = 1\text{-}e^{-\lambda t}$

where:

$D(t)$— degree of degradation,

λ— oefficient characterizing the degradation rate,

t — service (operational) time.



This model allows a qualitative assessment of the temporal development trends of the degradation process. When the results of sensor monitoring are analyzed together with this model, the service life of structural elements and the stages of deterioration in their technical condition can be identified.

Integral Indicator of Technical Condition. To perform a comprehensive assessment of a building's technical condition, an integral indicator that summarizes individual parameters is used. This indicator is determined by the following expression:

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$S = \sum_{i=1}^{n} w_i * P_i$

where:

P_i — individual monitoring parameters such as deformation, vibration, and environmental effects,

w_i — weighting coefficients representing the significance of these parameters.

The integral indicator allows a unified and systematic assessment of the technical condition. If this indicator falls below a specified critical threshold, the building or structure is considered to be approaching a technically hazardous state. This approach enables the use of monitoring results in making informed operational decisions.

Conclusion

This study demonstrated the scientific and practical validity of the mathematical modeling approach based on sensor monitoring for assessing the technical condition of buildings and structures. Data obtained from monitoring systems on deformation, vibration, and environmental parameters allow for an accurate representation of the mechanical state of structural elements under real operational conditions. The mathematical models applied within the study enabled a systematic analysis of deformations and dynamic processes occurring in structural elements. This approach highlighted the limitations of assessing technical condition solely through visual inspections or periodic examinations and scientifically substantiated the advantages of continuous monitoring. Analyses based on sensor data make it possible to detect latent and slowly developing adverse processes within structures.

The findings indicate that assessing technical condition through mathematical modeling contributes to enhancing the operational safety of buildings and structures. The application of monitoring results in conjunction with predictive models allows for evaluating future trends in technical condition and planning preventive measures in advance, which is crucial for preventing emergency

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situations. Moreover, the approach applied in this study provides a methodological basis for integration with BIM and Digital Twin technologies. By linking real data from sensors with digital models, it becomes possible to monitor and analyze the technical condition of buildings in real-time during their operational lifecycle. This integration could have significant scientific and practical implications for the development of smart building and digital city concepts in the future.

Overall, the approach based on sensor monitoring and mathematical modeling can be considered a modern, reliable, and promising method for assessing the technical condition of buildings and structures. The results of this study serve as a solid theoretical foundation for future scientific research and practical projects in this field.

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