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High rise building steel structure monitoring and energy efficiency optimization based on BIM and strain sensor vibration signal processing

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Abstract

With the acceleration of urbanization, the wide application of high-rise buildings puts forward higher requirements for the safety and energy efficiency of building structures. The traditional monitoring methods are difficult to meet the real-time and accurate evaluation of the dynamic performance and energy consumption of steel structures. Based on building information modeling (BIM) and strain sensor, this paper discusses the vibration monitoring and energy efficiency optimization of steel structures in high-rise buildings. In this paper, BIM technology is used to build a three-dimensional building model, and dynamic monitoring is carried out with strain sensors to obtain real-time vibration signals. The characteristic parameters are extracted by signal processing technology, and the energy consumption performance of buildings under different operating conditions is analyzed. The monitoring data is combined with a comprehensive assessment of the building design to identify the key factors affecting energy efficiency. The research results show that the monitoring of BIM and strain sensors can effectively identify the vibration characteristics of buildings under different environmental and load conditions, and then reveal its impact on energy consumption. Optimization measures include improving structural design and material selection, and adopting intelligent control strategies. These measures not only improve the safety of buildings, but also significantly improve energy efficiency.

Keywords: BIM; Strain sensor; Vibration signal processing; High-rise buildings; Steel structure monitoring; Energy efficiency optimization

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1. Introduction

In the context of global response to climate change and resource shortage, the construction industry is facing increasingly severe challenges to improve energy efficiency. As the building form with the highest land use density in the city, high-rise building has become a big energy consumer because of its unique structural characteristics and use requirements. Not only do these buildings consume a lot of energy during construction, there are also concerns about energy consumption such as electricity, heating and cooling required for their daily operations. Therefore, improving the energy efficiency of tall buildings has become an important indicator to measure their sustainability and environmental friendliness. With the continuous progress of building technology, building information modeling (BIM), as an integrated information management tool, has been widely used in the stages of building design, construction and operation. BIM can fully reflect the physical and functional characteristics of buildings through digital means, and provide data support for the life cycle management of

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buildings. However, the traditional BIM technology still has shortcomings in the dynamic performance monitoring and energy consumption analysis of high-rise buildings in actual use. In order to better monitor and optimize the energy consumption performance of buildings, it is particularly important to combine dynamic monitoring technology.

Building Information Modeling (BIM) technology combines information from various stages of architectural design, construction, and management, achieving comprehensive collaboration and integration, which helps to improve the efficiency and quality of building projects [1]. Steel frame is an important structural component of high-rise buildings, mainly responsible for supporting the overall weight and resisting external wind loads [2]. However, due to the complexity and particularity of high-rise buildings, such as earthquakes, wind forces, temperature changes, etc., structural deformation, fatigue, and damage can occur, even leading to safety hazards. In order to timely detect and handle abnormal changes in the steel structure of high-rise buildings, strain sensor vibration signal processing technology is widely used in high-rise building monitoring systems [3]. By deploying strain sensors in key parts of the steel structure to monitor the stress situation of the steel structure under different working conditions, the deformation and stress distribution of the structure can be obtained in real time. This helps to timely detect potential structural problems, take measures for repair and reinforcement in advance, and avoid situations that may cause safety hazards. Vibration signal processing technology conducts real-time analysis of parameters such as vibration frequency and amplitude of steel structures [4]. By combining BIM technology, real-time integration of data collected by sensors with BIM models can achieve three-dimensional visualization monitoring of structural states [5]. Engineers and managers can understand the real-time condition of building structures through an intuitive interface, achieving comprehensive monitoring of the structural status.

The combination of strain sensor vibration signal processing technology and BIM technology designed in this article provides a more comprehensive and effective solution for the construction and operation of monitoring systems. Strain sensor vibration signal processing technology can achieve real-time monitoring of strain and vibration signals of steel structures, thereby helping engineers understand the structural stress, deformation, and vibration status, timely identify problems, and take corresponding measures [6]. This technology can provide accurate data support, making monitoring more accurate and reliable. By combining BIM technology, the data collected by sensors can be integrated with the building information model to achieve three-dimensional visualization monitoring of the structural state [7]. By introducing advanced monitoring technology and information technology, we can better safeguard urban construction and ensure a more stable and safe living and working environment for people [8].

2. Related work

With the global trend of increasing attention to energy efficiency, the energy consumption of the construction industry, especially high-rise buildings, has gradually become the focus of academic and industrial attention. Because of its unique structural characteristics and use requirements, high-rise buildings are often faced with complex energy management challenges. Therefore, many researchers have begun to explore various technical means to improve the energy efficiency of tall buildings, especially in structural monitoring and dynamic performance analysis. Building Information Modeling (BIM) technology, as an important tool of modern architectural design, has been paid more and more attention. By creating digital 3D models of buildings, BIM provides rich information management capabilities to help designers, construction units and owners make better decisions throughout the building life cycle. The research of Deng et al. (2019) shows that the application of BIM can effectively reduce the error rate in the architectural design process, improve the construction quality, and thus reduce energy consumption to a certain extent. BIM can also be used to predict and optimize building energy consumption through energy efficiency analysis tools. These advantages make BIM an important basis for achieving energy efficiency improvements in tall buildings. With the rapid development of sensor technology, strain sensors are gradually introduced into the monitoring of buildings. The strain sensor can monitor the vibration of building structure in real time and provide reliable data support for structural health monitoring. Relevant studies have shown that the monitoring scheme based on strain sensor can effectively identify key structural parameters, such as vibration frequency and strain characteristics, so as to reveal the energy consumption behavior of the structure under different use states. Literature points out that the analysis of the relationship between vibration signals and building energy consumption can provide objective basis for energy management of high-rise buildings and help design effective optimization measures.

In recent years, the research on the combination of BIM and sensor technology has gradually increased. By combining the BIM model with real-time monitoring data, not only can the dynamic performance analysis of the building structure be realized, but also the real-time assessment of energy consumption can be carried out. Literature research results show that the monitoring system integrating BIM and strain sensor can effectively integrate the dynamic response of buildings with energy consumption data, providing a new perspective for building energy efficiency optimization. This integrated approach not only improves the reliability of data, but also provides the basis for intelligent management of buildings. By using vibration signal processing technology to analyze the monitoring data, the energy consumption mode of high-rise buildings in use can be deeply discussed. It is pointed out that the intelligent prediction of building energy consumption can be realized by combining the feature extraction of vibration signal with machine learning algorithm. This approach has achieved positive results in several high-rise building projects, not only improving the efficiency of facility management, but also providing strong support for later maintenance. At present, the current research on the combination of BIM and sensors mostly focuses on data acquisition and model establishment, while relatively little attention is paid to the in-depth analysis of data and optimization decision. The energy consumption characteristics of different types of high-rise buildings are different, and the existing optimization model may not be universally applicable. Therefore, customized research and optimization measures for specific building characteristics will be the focus of future research.

The collaborative effect of literature enables designers to more efficiently create refined design schemes, laying a solid foundation for subsequent processing and construction [9]. The use of Solidworks in literature for material cutting guidance not only improves processing efficiency and accuracy, but also effectively controls material waste. Before processing, simulating the layout and installation of complex components through BIM models can effectively eliminate possible construction problems in advance, ensure the welding quality and accuracy of components, and ensure that they meet design requirements [10]. This intelligent acceptance method not only improves the efficiency and reliability of acceptance, but also provides more technical support for quality control, which is conducive to ensuring project progress and quality while saving materials and costs. Literature evaluation of the role of BIM technology in construction schedule control, construction plan optimization, resource coordination, and other aspects helps project teams better manage construction progress and improve their ability to control engineering progress [11]. The indicator system for quality and efficiency focuses on assessing the application of BIM technology in design collaboration, quality control, and construction process improvement, in order to improve the quality and reliability of construction projects and reduce engineering quality risks. In terms of cost-effectiveness, literature focuses on the effectiveness of BIM technology in cost control, resource utilization efficiency, cost risk management, and other aspects, helping project teams achieve precise cost control, optimize resource utilization, reduce engineering costs, and improve economic benefits [12]. The indicator system for safety and efficiency mainly tests the effectiveness of BIM technology in construction safety management, risk identification and prevention, and construction site safety monitoring, providing technical support to ensure construction site safety and reduce construction risks. The literature utilizes BIM technology to develop safety management plans, improve construction safety levels, and ensure the safety of workers and projects [13]. In terms of management efficiency, BIM technology has brought more efficient information management, decision support, and team collaboration methods to project management, promoting team collaboration, strengthening information sharing and communication, and improving overall project management efficiency and quality [14]. The literature fully utilizes the advantages of each software to solve the problems of complex steel structures with variable spatial relationships, complex cross-sectional forms, and numerous parts, thereby achieving high-precision deepening design and generating detailed drawings. In literature, AutoCAD, as a universal drawing software, can provide flexible drawing tools and wide file compatibility, helping to quickly draw floor plans and display images [15]. Through SolidWorks, precise modeling of steel structures with complex cross-sectional forms and numerous components can be achieved. The literature suggests that Tekla Structures is a BIM software specifically designed and modeled for steel structures, with powerful steel structure modeling and analysis capabilities [16]. Tekla Structures can handle complex spatial positional relationships, connections and detailed design of various steel structural components, helping to achieve refinement and deepening of steel structure design.

3. Application and Benefit Analysis of BIM Technology

3.1. Collaborative modeling

When using Revit software to build high-rise building BIM models, the workset mode, also known as the central file mode, is a common collaborative design approach. Follow the collaborative modeling process of the working set shown in Figure 1.

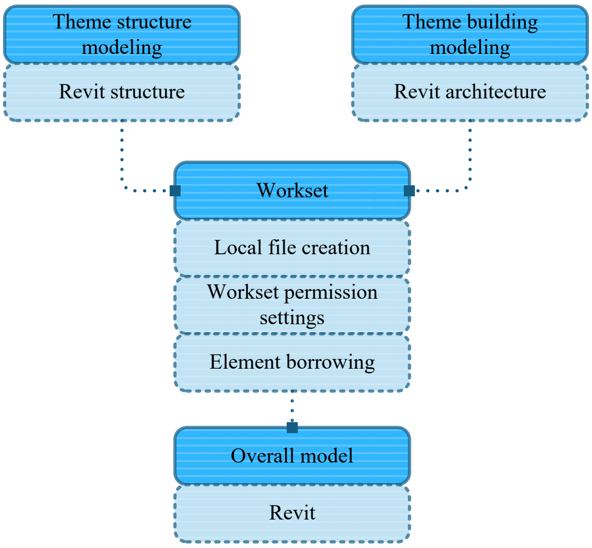

Figure 1. Workset Collaborative Modeling Process

3.2. Node deepening

Firstly, it is necessary to conduct a detailed inspection of the received design documents, including design specifications and drawings related to design changes. This can help identify potential issues and inconsistencies, provide support for modeling work, and avoid unnecessary modifications and delays in the future. Breaking down the preliminary modeling work into different parts, such as dividing it by functional areas, floors, or systems, helps to better organize and manage the modeling work. Meanwhile, drawing template data can provide consistent benchmarks, facilitating subsequent modeling work. Define color requirements for modeling components to help distinguish different component types or functions, better meeting subsequent management and visualization needs. Clear color definitions can improve the readability and usability of the model. Based on the installation sequence, determine the deepening operation sequence of the construction drawings, which helps to avoid errors or process conflicts during the construction process and ensure smooth construction. By clearly deepening the sequence of tasks, subsequent problems and adjustments can be reduced, and construction efficiency can be improved.

During the design process, segmenting the truss using BIM can help control structural stability, reduce lifting frequency, and ensure smooth component processing on site. When dividing, it is necessary to consider factors such as component size, weight, and section position to meet road transportation requirements, transportation performance requirements, and convenience of on-site construction operations. Through the segmented processing of BIM software, it is possible to better manage and display information on various components of the truss, such as their specifications, materials, quantities, and weights. Table 1 shows the specific information of different components.

Table 1. F48M-F51 truss section information table

Component Name	Total weight (t)	Maximum unit weight (t)	Weld length (m)
Steel columns	1803.06	81.44	167.91
Diagonal bar	557.09	22.85	304.99
Upper chord	555.13	37.68	151.69
Mid chord	35.26	2.00	20.03
Lower chord	249.01	16.12	154.14

3.3. Determination of Benefit Weights

In project benefit evaluation, a reasonable allocation of indicator weights can ensure that the evaluation results are more objective and accurate. Constructing a comparative discriminant matrix is a method used to analyze the relative importance between multiple elements. Using a pairwise comparison method, the importance of different elements in each layer relative to the elements in the previous layer is determined using a scale of 1 to 9. This is achieved through formula (1):

$$\bar{a}_{ij} = a_{ij}/\sum_{i=1}^{n} a_{ji}, i, j = 1,2, \dots, n \tag{1}$$

Sum the normalized matrix according to formula (2):

$$\widetilde{W}_i = \sum_{j=1}^{n} \bar{a}_{ij}, i = 1,2, \dots, n \tag{2}$$

Due to the complexity of objective things, people's judgments are often subjective, and each comparison and judgment cannot fully require the same thinking standards. Although it is not required that the judgments be completely consistent, if the comparison judgment matrix lacks logical coherence, it may lead to decision errors. Therefore, it is desired to maintain general consistency in judgment, which requires consistency testing. Firstly, calculate the maximum eigenvalue of the judgment matrix, which can be achieved through formula (3):

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n} \frac{(A \cdot W)_i}{w_i} \tag{3}$$

The random consistency indicators for different scales are different. In order to evaluate whether the judgment matrix has reasonable consistency, the consistency ratio CR is introduced, which is calculated using formula (4):

$$CR = \frac{CI}{RI} \tag{4}$$

3.4. Fuzzy comprehensive evaluation of benefits

By using the Analytic Hierarchy Process to stratify the BIM technology benefit indicators, the importance relationship between indicator factors can be obtained, which helps decision-makers better understand the weight allocation of various indicators in BIM technology benefit evaluation. However, the Analytic Hierarchy Process (AHP) often cannot achieve an overall evaluation of the BIM technology benefits of a single project, so it is necessary to introduce the fuzzy comprehensive evaluation method for improvement. The ultimate goal is to evaluate the effectiveness and benefits of BIM technology application, provide important reference basis for construction parties and decision management personnel, and promote the widespread application of BIM technology.

The factor set established based on the benefit evaluation index system can be displayed using formula (5).

$$U = \{u_1, u_2, \cdots, u_n\} \tag{5}$$

Before establishing the fuzzy relationship matrix, it is necessary to first count the number of experts evaluating the level, convert these evaluation results into matrix form, and obtain the membership matrix of the evaluation level, as shown in formula (6).

$$R = \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_m \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & \cdots & R_{1n} \\ R_{21} & R_{22} & \cdots & R_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ R_{m1} & R_{m2} & \cdots & R_{mn} \end{bmatrix} \quad (6)$$

Use formula (7) to obtain a comprehensive evaluation result of the BIM technology benefits of the entire project.

$$S = W \circ R = (w_1, w_2, \cdots, w_m) \circ \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}$$
(7)

In this study, the S-vector reflects the comprehensive membership degree of the BIM technology benefit evaluation of the evaluated super high-rise buildings, providing decision-makers with comprehensive and accurate evaluation results, helping them better grasp the application effect and potential benefits of BIM technology.

4. Vibration signal processing method for steel structure strain sensors

4.1. Principle of strain sensors

Assuming that the cross-section of the resistance wire is circular, with a diameter of D, an area of A, and an initial resistance value of R, it can be calculated according to formula (8):

$$R = \rho \frac{L}{A} \quad (8)$$

The relative variation of resistance wires can be represented by formula (9):

$$\frac{dA}{A} = 2\frac{dD}{D} = -2\mu\frac{dL}{L} \quad (9)$$

The strain is represented by formula (10):

$$\varepsilon = \frac{dL}{L} \quad (10)$$

The change in resistance value is calculated according to formula (11):

$$\frac{dR}{R} = \frac{d\rho}{\rho} + \frac{dL}{L} - \frac{dA}{A} = \frac{d\rho}{\rho} + (1 + 2\mu)\varepsilon \quad (11)$$

The relative resistance change of the resistance wire is proportional to the relative change in the axial length of the wire, expressed by formula (12):

$$\frac{dR}{R} = K_s\varepsilon \quad (12)$$

Among them:

$$K_s = \frac{1}{\varepsilon}\frac{d\rho}{\rho} + (1 + 2\mu) \quad (13)$$

By modeling and analyzing the response of metal materials under external forces, better monitoring and control of structural strain and deformation can be achieved.

4.2. Stochastic resonance inversion

Brownian particles are driven by external periodic excitation forces s(t) and Gaussian white noise n(t), and their state can be expressed by the Langevin equation as formula (14):

$$\frac{dx}{dt} = -\frac{dU}{dx} + s(t) + n(t) \quad (14)$$

The target signal s(t) is expanded into a Fourier series, and formula (15) provides the expanded form.

$$s(t) = a_0/2 + \sum_{k=1}^{\infty} \left(a_k\cos(k\omega_0 t) + b_k\sin(k\omega_0 t)\right) \quad (15)$$

Among them:

$$\cos(0) = 1, \sin(0) = 0$$

$$a\cos x + b\sin x = (a^2 + b^2)^{1/2}\sin(x + \varphi) \quad (16)$$

$$\tan\varphi = a/b$$

Substitute formula (16) into formula (15). Through this substitution, the expression for formula (17) is obtained.

$$s(t) = \sum_{k=0}^{\infty} c_k\sin(k\omega_0 t + \varphi_k)$$

$$c_k = (a_k^2 + b_k^2)^{1/2}, \tan\varphi_k = a_k/b_k, \varphi_0 = \pi/6$$
(17)

Formula (17) gives the projection of the target signal s(t) on a sinusoidal function of frequency ω. Assuming that the frequency of the target signal can be detected by a stochastic resonance detector, formula (18) gives a representation of the frequency of the target signal.

$$\tilde{s}(t) = \beta(1)\cos(2\pi f_1 t + \beta(2)) \quad (18)$$

By using a random resonance detector to detect the frequency of the target signal and representing it as a variable in formula (18).

4.3. Identification of vibration modal parameters

The vibration based damage identification method is a global identification technique, with the core idea that damage can affect the physical properties of the structure, which are closely related to the vibration characteristics of the structure. By analyzing the changes in structural vibration characteristics, it can be inferred whether there is damage to the structure. By analyzing the vibration modes of the structure, damage in the structure can be visually detected. Modal analysis is a vibration based global dynamic testing method widely used in structural state assessment and health monitoring, typically conducted under operating or external load conditions. Traditional modal analysis requires manual vibration equipment, such as impact hammers and vibrators, which is called experimental modal analysis (EMA); Operational Mode Analysis (OMA) relies on actual operating conditions and loads to identify modal parameters.

For a damped vibration system with N degrees of freedom, the control differential motion equation can be analyzed using the following formula:

$$M\ddot{y}(t) + C\dot{y}(t) + Ky(t) = f(t) \quad (19)$$

Based on modal expansion theory, the vibration response can be decomposed into the following formula:

$$x(t) = \Phi q(t) = \sum_{i=1}^{n} \varphi_i q_i(t) \tag{20}$$

For free vibration, when the external force F(t)=0, the transient vibration of a lightly damped system can be expressed as:

$$q_i(t) = u_i e^{-\xi_i \omega_i t} \cos(\omega_{di} t + \theta_i), i = 1, \cdots, n \tag{21}$$

The relationship between modal natural frequency and parameters satisfies the following:

$$\omega_{di} = \omega_i \sqrt{1 - \xi_i^2} \tag{22}$$

4.4. Sensitivity of structural parameters

In order to identify the parameters of damaged steel structures, the dynamic response sensitivity of unknown parameters is first obtained using numerical integration method, forming a sensitivity matrix; Then use the penalty function method to iteratively solve the regularization problem; Finally, identify local damage to the structure directly from the measured dynamic response. According to finite element theory, the structural vibration equation under external forces can be expressed as:

$$M\ddot{d} + C\dot{d} + Kd = F(t) \tag{23}$$

In order to solve the sensitivity matrix of structural response to element stiffness, the partial derivative of the stiffness of the i-th element is solved using formula (24) of the vibration equation.

$$M\frac{\partial \ddot{d}}{\partial E_i} + C\frac{\partial \dot{d}}{\partial E_i} + K\frac{\partial d}{\partial E_i} = -\frac{\partial K}{\partial E_i} d - a_2 \frac{\partial K}{\partial E_i} \dot{d} \tag{24}$$

The numerical integration method is used to calculate the dynamic response of the structure. The dynamic response of the structure calculated by formula (23) is substituted into formula (24), and the partial derivative of the stiffness of each element with respect to the structural response is calculated to obtain the response sensitivity matrix S.

$$S = \begin{bmatrix} \frac{\partial R^i(t_1)}{\partial E_1} & \frac{\partial R^i(t_1)}{\partial E_2} & \frac{\partial R^i(t_1)}{\partial E_3} & \cdots & \frac{\partial R^i(t_1)}{\partial E_N} \\ \frac{\partial R^i(t_2)}{\partial E_1} & \frac{\partial R^i(t_2)}{\partial E_2} & \frac{\partial R^i(t_2)}{\partial E_3} & \cdots & \frac{\partial R^i(t_2)}{\partial E_N} \\ \frac{\partial R^i(t_3)}{\partial E_1} & \frac{\partial R^i(t_3)}{\partial E_2} & \frac{\partial R^i(t_3)}{\partial E_3} & \cdots & \frac{\partial R^i(t_3)}{\partial E_N} \end{bmatrix} \tag{25}$$

4.5. Damage detection effect

Wavelet denoising and feature extraction were performed on the sample signals collected by the sensors, and the wavelet packet energy values of each sample signal in 16 frequency bands were obtained. The results are shown in Table 2.

Table 2. Energy Feature Extraction of Wavelet Packets in Sensor Sampling Signals

Frequency band	1	2	...	100	...	200
1	0.2189569	0.1969290	...	0.4945699	...	0.2383671
2	0.1959824	0.3769427	...	0.2188604	...	0.1784808
3	0.2918445	0.1983497	...	0.0478814	...	0.0869297
4	0.0792273	0.0525336	...	0.0712893	...	0.3223247
5	0.0762535	0.0283183	...	0.0137229	...	0.0187149
6	0.0837485	0.0345917	...	0.0203468	...	0.1309630
7	0.1076357	0.0341300	...	0.0244220	...	0.0509305
8	0.0347299	0.0139686	...	0.0224635	...	0.0377740
9	0.0107988	0.0107988	...	0.0075060	...	0.0049614
10	0.0042590	0.0082438	...	0.0074749	...	0.0039486
11	0.0041941	0.0056101	...	0.0103553	...	0.0089557
12	0.0047794	0.0056872	...	0.0087146	...	0.0055674
13	0.0010125	0.0042236	...	0.0136682	...	0.0019750
14	0.0082853	0.0047367	...	0.0123620	...	0.0067389
15	0.0055968	0.0042504	...	0.0120761	...	0.0077666

Table 3 lists the parameters and installation locations of the sensor, including its wavelength (in nm), sensitivity (in nm/g), and installation location. FBG sensor is a fiber optic sensor based on the principle of Bragg grating, which monitors environmental parameters by measuring the wavelength change of reflected light in the grating.

Table 3. FBG sensor parameters and installation location

sensor	Wavelength (nm)	Sensitivity (nm/g)
Al	1528.452	0.338
A2	1550.140	0.357
A3	1552.699	0.345
A4	1559.420	0.326

For the discrete model nodes of a damaged simply supported beam steel structure, it is necessary to extract the acceleration response at the nodes and simulate the noise as Gaussian white noise:

$$\ddot{d}_j^n(t) = \ddot{d}_j(t) + n(t) \tag{27}$$

During the processing, a small allowable value can be set to determine whether the relative value of the processing result has reached the ideal state.

$$\left\|\frac{E_{K+1}-E_K}{E_{K+1}}\right\| \le T \tag{28}$$

According to the unit numbers, real elastic modulus, and identified elastic modulus data listed in Table 4, it can be seen that the error range between the identified elastic modulus and the real elastic modulus is within a small error range, indicating a good identification effect on the damage at that location. The identification results obtained through 16 iterations indicate that this method has high accuracy and reliability in identifying local damage in structures.

Table 4. Reduce unit modulus by 10%

Unit number	True elastic modulus (GPa)	Identifying elastic modulus (GPa)	Identification error
1	200.00	198.895	0.553%
2	200.00	200.623	-0.312%
3	200.00	200.541	-0.270%
4	200.00	198.862	0.569%
5	180.00	178.008	1.107%
6	200.00	202.116	-1.058%
7	200.00	201.191	-0.596%
8	200.00	199.494	0.253%

5. Design of Steel Structure Monitoring System for High rise Buildings

5.1. System design

Figure 2 shows the overall design of the steel structure monitoring system for high-rise buildings, including the structural framework and functional modules of the monitoring terminal and cloud platform, reflecting the workflow and information exchange mode of the entire system. The design of the steel structure monitoring system for high-rise buildings mainly includes two parts: software and hardware design of the monitoring terminal and cloud platform development. The monitoring system detects and identifies the degree and location of structural damage to evaluate its impact on structural integrity. The Internet of Things technology plays an important role in structural health monitoring systems, providing real-time monitoring and data transmission capabilities. The design of the monitoring terminal aims to collect and transmit structural vibration data, and provide a user-friendly interface for real-time monitoring of structural conditions. The design of the entire system should consider factors such as data security, real-time performance, and reliability.

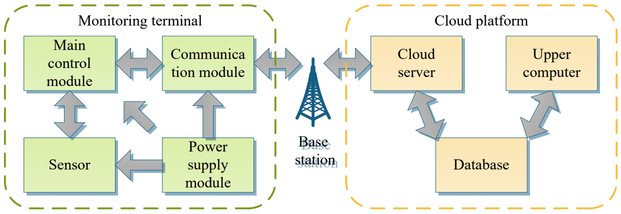

Figure 2. Overall design of steel structure monitoring system for high-rise buildings

The main control module is the core part of the monitoring terminal, responsible for controlling the operation of the entire system and coordinating communication between various modules. Through pre burned programs in internal memory, the main control module can achieve functions such as data input and output, data processing, and storage management. Each communication module needs to be paired with a SIM card to establish a connection with the network base station and achieve remote transmission of monitoring data. Through such a high-speed and stable communication module, it is possible to ensure real-time monitoring and transmission of structural vibration data by the monitoring system.

5.2. Software Architecture

As shown in Figure 3, the software design of the steel frame structure monitoring system for high-rise buildings mainly involves four key parts: monitoring terminal driver program design, server-side database construction, upper computer program development, and Matlab data analysis program design. These parts together constitute the complete software system of the monitoring system, each undertaking different functions and tasks.

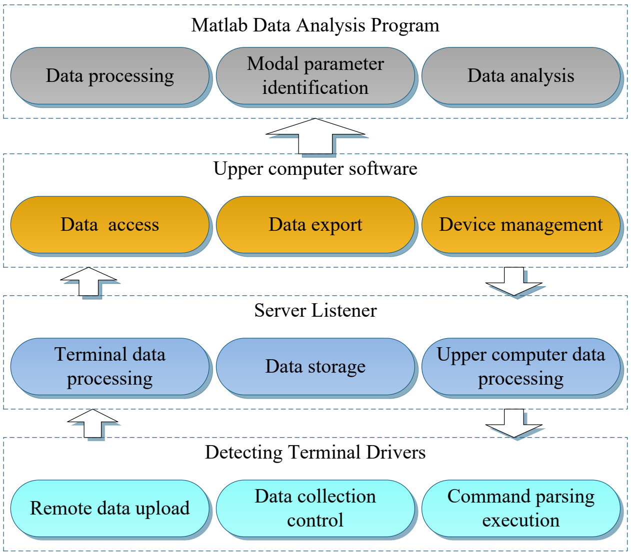

Figure 3. The overall structure of monitoring system software

Data collection is responsible for determining when to obtain raw data based on preset collection intervals or thresholds. The uploaded data needs to be encrypted or other security measures to protect the integrity and confidentiality of the data, ensuring the security and reliability of data transmission. The command parsing execution module parses control commands from the server side and executes corresponding operations. The command parsing and execution module needs to ensure accurate parsing and timely execution of commands to ensure that the system can regulate and operate as needed.

In the monitoring system of high-rise building steel structure based on the Internet of Things, the server is responsible for handling the communication between the monitoring terminal and the upper computer. The server-side listener, as an object-oriented application, undertakes multiple key tasks. The listener ensures that the server-side can timely obtain monitoring data and effectively store and manage it, providing a necessary foundation for subsequent data analysis and processing. The listening program is responsible for receiving notifications and commands from the upper computer. By saving operation commands in the database, the server listening program can timely read these commands and package them in communication frame format before sending them to the monitoring terminal, achieving remote control of the steel structure monitoring system for high-rise buildings. This design scheme achieves fast and reliable data transmission and command control, improving the real-time and reliability of the system.

5.3. Stress changes before and after optimization

Select appropriate analysis methods based on the basic characteristics of the vibration signals obtained from testing. The commonly used power spectrum method currently assumes that the signal is a stationary random signal. Therefore, before processing the vibration signal, determining whether the signal is stationary directly affects the selection of subsequent analysis methods. The stress values of each sensor layout point are shown in Table 5.

Table 5. Comparison table of stress distribution points of sensors before and after modification of steel beams

number	Stress value before cutting/MP	Stress value after cutting/MP
1	21.792	25.330
2	33.361	27.636
3	45.688	32.889
4	58.776	41.626
5	37.560	79.030
6	27.598	32.628
7	54.323	59.884
8	71.630	73.407

These differences are usually caused by the uncertainty or approximation of the selected material mechanical performance parameter values during the calculation process, which originates from factors such as the measurement accuracy of material performance parameters, the accuracy of model assumptions, and the simplification of calculation methods.

Table 6. Comparison Table between Theoretical and Actual Strain Changes at Sensor Layout Points

Sensor number	Theoretical value of strain change/µs	Strain variation measured value/µe	Identification error
1	17.456	14.872	14.802%
2	-28.572	-33.530	-17.350%
3	-62.349	-65.109	-4.427%
4	-78.875	-84.859	-7.587%
5	202.028	197.101	2.439%
6	23.484	20.708	11.820%
7	21.951	21.604	1.581%
8	10.919	5.781	47.053%

As shown in Table 6, by combining finite element analysis and measured data, the performance and safety status of the structure can be comprehensively evaluated. Real time monitoring can capture structural changes in a timely manner, while finite element analysis provides a deeper understanding of structural behavior. By combining theoretical calculations with measured data, the working state of the structure can be more accurately evaluated, providing reliable guidance and support for practical engineering.

6. Conclusion

As the global focus on sustainable buildings and energy efficiency continues to grow, vibration signal processing technologies based on BIM (Building Information Modeling) and strain sensors offer new opportunities for energy efficiency optimization in tall buildings. By combining the powerful data management and visualization capabilities of BIM with the real-time monitoring capabilities of strain sensors, the construction industry can achieve a deep understanding of the dynamic behavior of structures and develop more scientific and rational energy efficiency optimization strategies. The application of BIM technology enables the design and construction phase to proactively consider energy consumption issues, and identify and optimize potential energy consumption hotspots through energy efficiency simulation and analysis. This process not only reduces energy consumption during the operational phase, but also improves the overall quality of the building design. Combined with strain sensors, the vibration characteristics of building structures can be monitored in real time under different operating conditions, which provides important data support for energy efficiency analysis. This dynamic feedback mechanism, based on real-time data, allows buildings to adapt to environmental changes at any time and optimize energy performance. The introduction of vibration signal processing technology can effectively analyze the energy consumption pattern of buildings in the process of use, and form a more accurate energy consumption prediction model. Such models not only help building managers understand building performance in real time, but also support data-based decision-making, making energy management smarter and more efficient. Through continuous monitoring and analysis, building managers can quickly identify energy consumption anomalies, perform maintenance and optimization in a timely manner, and ensure that the building maintains an efficient level of energy use throughout its life cycle. The integrated approach based on BIM and strain sensor technology not only strengthens the monitoring ability of structural health, but also lays the foundation for the development of smart buildings in the future. With the development of the Internet of Things and artificial intelligence technology, further integration of multiple sensor data will drive innovation and optimization in energy management of high-rise buildings. Therefore, with the help of BIM technology and strain sensor vibration signal processing technology, the high-rise building steel structure monitoring system can not only improve monitoring efficiency, but also enhance monitoring accuracy and warning ability, thereby better ensuring the safe operation and lasting stability of high-rise building structures. This integrated monitoring system is not only of great significance for current construction projects, but also provides useful reference and exploration for the development of future building safety monitoring fields.

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