Building Structure Construction Simulation and Structural Safety Analysis Based on BIM Technology

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Abstract: With the rapid growth of the construction industry and continuous innovation in engineering technology, steel structure buildings have become an important form in modern building systems. In this context, Building Information Modeling (BIM) technology, with its powerful data integration and collaborative management capabilities, is gradually playing a key role throughout the entire lifecycle of buildings. BIM can efficiently integrate massive heterogeneous data from multiple sources generated during the construction process, achieving visual, graphical, and interactive management of the construction process, and demonstrating significant advantages in building structure construction simulation. This article studies the simulation of construction process and structural safety analysis methods for building structures based on BIM technology. By constructing high-precision three-dimensional (3D) BIM models and integrating time dimensions to form four-dimensional (4D) construction simulations, dynamic visualization of construction progress and procedures has been achieved, which helps to identify potential construction conflicts and safety hazards in advance. At the same time, applying BIM visualization technology to architectural structure design can achieve real-time sharing and collaborative optimization of design data and solutions, significantly improving the scientific and rational nature of design.

1. Introduction

In recent years, the construction industry has undergone a profound technological transformation, and the widespread application of digital and information technology has significantly improved the management efficiency and execution level of engineering construction [1]. With the acceleration of urbanization and the continuous emergence of large-scale infrastructure projects, the construction process is becoming increasingly complex, and traditional management models are no longer able to meet the demands of modern engineering for refinement, efficiency, and intelligence [2]. In this context, visualization technology has gradually gained widespread attention as an important means to enhance construction management capabilities. Through visualization methods, key elements such as construction progress, cost control, resource allocation, and energy consumption can be dynamically monitored and optimized, thereby achieving scientific decision-making and lean management throughout the entire project process [3]. The rise of BIM technology provides strong technical support for the digital transformation of the construction industry. BIM not only enables the integration and sharing of heterogeneous data from multiple sources throughout the entire lifecycle of a building, but also builds an information platform that supports multi-party collaborative work [4].

At each stage of the project, personnel from all parties can insert, extract, update, and modify project information in real time through the BIM platform, ensuring the precision and timeliness of information transmission, achieving efficient collaboration among all parties involved, and promoting seamless connection from planning to delivery of the construction project [5]. Especially during the construction phase, BIM technology can combine 3D geometric models with construction schedules to build a 4D construction simulation system, which introduces a time dimension based on the 3D spatial model to achieve dynamic visualization of the construction process [6]. This simulation method that integrates spatiotemporal information can not only visually

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present the operational status of each construction stage, but also identify process conflicts, resource bottlenecks, and spatial interference in advance, providing scientific basis for optimizing construction organization and risk prevention [7]. However, despite the enormous potential of BIM technology in construction simulation, there are still many challenges in its current application. Most construction plan simulation systems have a low level of intelligence, unclear expression of key construction elements, and a disconnect between simulation results and actual construction, resulting in poor implementation [8].

Especially when facing large-scale municipal projects or super high-rise buildings in complex environments, traditional BIM simulation methods are inadequate in terms of data processing capabilities, interactivity, and real-time performance. The common visual simulation methods currently include 3D scene construction based on augmented reality (AR) and interactive modeling technology based on OpenGL. Among them, although AR technology can achieve an immersive experience of virtual real integration, it is limited by hardware devices and scene scale, and is mostly suitable for small building projects, making it difficult to promote to large and complex projects; Although the modeling method based on OpenGL has strong graphics rendering capabilities, there are obvious shortcomings in information integration and collaborative management. In response to the above issues, this article focuses on the research of BIM based construction process simulation and structural safety analysis methods for building structures. By constructing high-precision 3D BIM models and integrating them with construction schedules to form a 4D construction simulation system, dynamic visualization of the entire construction process, resource allocation, and structural status can be achieved.

2. The Current Situation and Problems of Building Structure Construction Based on BIM

2.1 The Application of BIM Technology

BIM technology, as an emerging digital tool that integrates modern information technology with traditional construction project management concepts, is gradually becoming the core driving force for the transformation and upgrading of the construction industry [9]. BIM aims to manage the entire lifecycle of construction projects, running through various stages such as planning, design, construction, and operation, to achieve precise control over the entire project process. By constructing a multidimensional information model that includes geometric information, material properties, construction progress, cost data, etc., BIM not only enhances the transparency and collaboration of project management, but also demonstrates significant advantages in saving resources, reducing costs, improving efficiency, and promoting green and sustainable development. In practical applications, BIM technology, with its core characteristics of visualization, coordination, simulation, and optimization, greatly improves the quality and efficiency of construction projects. Its 3D modeling capability enables complex building structures and various components to be visually presented. Designers can use models to predict and optimize structural layout, pipeline arrangement, construction technology, etc. in advance, effectively avoiding problems such as "errors, omissions, collisions, and deficiencies".

At the same time, the BIM platform supports multi-party collaborative work, allowing owners, design units, construction units, and operation and maintenance teams to share and update data in a unified information environment, breaking down the barriers of traditional "information silos" and achieving efficient communication and collaboration across stages and disciplines [10]. It is particularly worth mentioning that BIM technology plays an irreplaceable role in the structural design of super high-rise buildings. Faced with super high-rise projects with complex structures, high construction difficulty, and high coordination requirements, traditional two-dimensional design is no longer able to meet the development needs of modern architecture. BIM based 3D collaborative design not only improves design precision and expression ability, but also enables dynamic control of construction progress and cost through 4D (3D+time) and 5D (+cost) simulations. In addition, BIM supports real-time monitoring and feedback during the construction process, enabling timely detection and correction of potential problems in design or construction, optimization of construction plans, and improvement of overall project safety and controllability. Therefore, the in-depth application of BIM technology is an important path to promote the intelligent, refined, and sustainable development of the construction industry.

2.2 Status and Problems

Currently, the application of BIM technology in simulating construction plans for building structures is becoming increasingly widespread, demonstrating enormous potential in enhancing construction visualization, optimizing construction organization, and strengthening multi-party collaboration. However, despite the gradual integration of BIM technology into the construction management process, its practical application still faces many practical problems and challenges, which restrict its deep promotion and effectiveness. Firstly, the existing mainstream BIM software still falls short in terms of functional integration and intelligence level. In the process of construction simulation, manual modeling, manual entry of schedule plans, and repetitive definition of construction processes are commonly relied upon, with a low degree of automation, resulting in long modeling cycles and delayed data updates. A large amount of manual intervention not only increases the workload but also reduces overall work efficiency. Secondly, construction projects involve multiple professional systems such as architecture, structure, mechanical and electrical engineering, and water supply and drainage. Each profession often designs independently, and there is a lack of effective communication and collaboration among designers, which can easily lead to problems such as component size deviation, mismatched connection methods, and spatial collisions, affecting construction feasibility and structural safety.

What is more prominent is that most BIM modelers are not experienced solution engineers with deep construction experience, and their understanding of construction processes, key construction nodes, resource allocation logic, etc. is not deep enough, which makes it difficult for the constructed BIM models to truly reproduce the on-site construction status during the simulation process. The key elements of construction simulation, such as process logic, mechanical scheduling, and manpower arrangement, are expressed vaguely, resulting in a lack of detailed support for simulation results, greatly reducing their credibility and practicality. In addition, traditional management models are still widely used in current construction site management, lacking dynamic and refined control mechanisms based on BIM. The layout, progress control, and emergency management of construction sites rely heavily on empirical judgment, and have weak ability to predict unexpected situations. At the same time, there is a lack of real-time data linkage between BIM models and actual construction progress, with model updates lagging behind, making it difficult for simulation results to effectively guide on-site operations, and even causing construction misunderstandings or operational errors.

3. Establishment of 4D Visualization BIM Model for Building Structure

3.1 Model Construction

The 4D visualization construction simulation of building structures is the integration and dynamic correlation of 3D BIM and construction schedule through the open interface of BIM software, in order to construct an organic virtual simulation system that integrates spatial and temporal dimensions. This model not only retains the geometric shape, spatial position, and physical properties (such as material properties, quality, dimensions, etc.) of the components contained in the 3D BIM model, but also introduces a time dimension (usually corresponding to the schedule arrangement in the construction schedule), achieving dynamic visualization of the construction process. The constructed 4D visualization model can be formally expressed as:

$$u(t) = f(x, y, z, t) \times n \quad (1)$$

In the formula, u is the mapping relationship between solid objects in the 4D visualization model of building structures; t is a time variable, corresponding to the time nodes in the construction schedule plan; f is the core function for constructing 4D visualization models; (x, y, z) is the 3D spatial coordinate, corresponding to the geometric position and spatial layout of each component in the building solid model; n is the number of building entities included in the 4D visualization model.

In the construction process of the 4D visualization model of building structures, a step function considering time factors is introduced to characterize the activation or participation state of components at specific time nodes. This step function is expressed in the form of a 4 × 4 homogeneous transformation matrix, which realizes the mathematical correlation between spatial coordinates and time evolution. It is a key mathematical tool for connecting three-dimensional geometric models with dynamic changes in construction progress. Collision detection, as a core component of 4D construction simulation, is mainly used to determine whether there is geometric interference or physical conflict between two or more building structural entities in space under specific construction sequences. Formula (2) is used to describe the homogeneous coordinate transformation matrix in the 4D visualization construction model, and its expression is as follows:

$$m = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix} \quad (2)$$

Among them, m is a step function that varies over time.

On this basis, formulas (3) and (4) further describe the spatiotemporal states of two different building structural entities in four-dimensional space, defining the relationship between their spatial positions and temporal attributes. When the time and spatial positions in these two formulas match, it indicates the existence of a collision.

$$\begin{cases} u(t_A) = f_A(x, y, z, t_A) \\ u(t_B) = f_B(x, y, z, t_B) \end{cases} \quad (3)$$

$$\begin{cases} t_A > 0 \\ |\min[u(t_A) - u(t_B)]| < d \end{cases} \quad (4)$$

In the formula, $|\min[u(t_A) - u(t_B)]|$ is the absolute value of the minimum distance between the spatial positions of building structure entities A and B at the corresponding time point, and parameter d is the preset allowable safety distance, which is the threshold for determining whether two building structure entities collide.

3.2 Experimental Analysis

This experiment takes a library construction project as the research object, which has the characteristics of narrow construction space, complex structure, and tight schedule, and puts forward high requirements for construction organization and safety management. To verify the effectiveness of the model, Table 1 compares the performance of the 4D visualization model constructed in this paper with traditional 3D BIM technology in terms of building structural safety. The results indicate that the 4D model can more accurately reflect the dynamic changes during the construction process, timely detect potential safety hazards in structural installation, cross operation, and temporary support, and significantly improve the safety control capability of the construction process. Compared to traditional 3D BIM technology that relies solely on static geometric information, 4D visualization models demonstrate stronger practicality and foresight in risk warning, process coordination, and safety decision support. Experimental results confirm that they have significant advantages in improving the safety of building structure construction.

Table 1 Precision of Hazard Identification/%

Construction content	4D visualization model	3D BIM
Structural installation	92.6	80.6
Cross operation	91.3	82.7
Temporary support	91.7	84.1

Figure 1 shows the schedule analysis results of the constructed 4D visualization construction model. By dynamically simulating the construction process in time and space, the model can clearly present the execution sequence, duration, and resource investment of each stage's work tasks, achieving precise control over the construction progress. The experiment used a real library project as a case study to compare the completion of the 4D model proposed in this paper with traditional 3D BIM technology under the same construction period conditions. The results indicate that in complex environments with limited construction space and frequent process intersections, construction organization based on 4D visualization models is more efficient and reasonable. The model can identify process conflicts in advance, optimize construction paths, and dynamically adjust resource allocation, thereby effectively improving job continuity and construction efficiency.

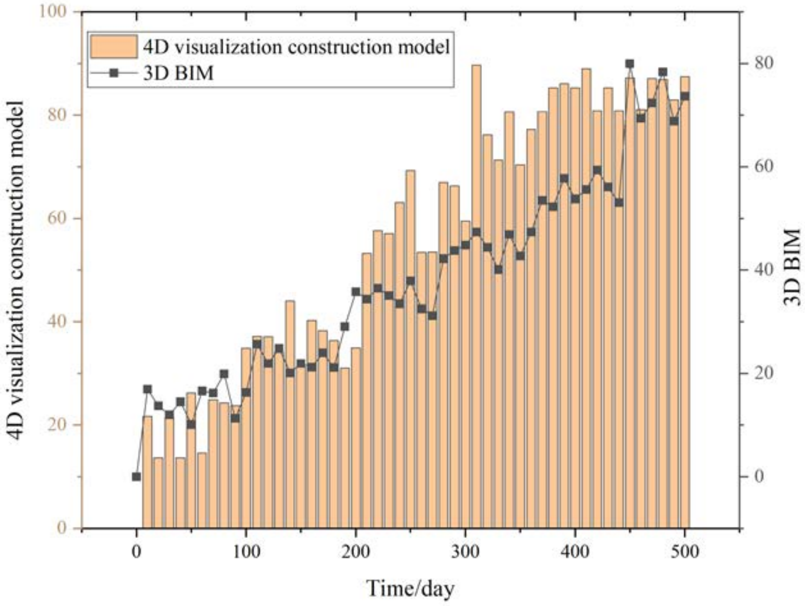

Figure 1 Progress plan analysis

4. Conclusions

This study systematically explores the practical application effect of building structure 4D visualization construction simulation model based on BIM technology in construction management. Research has shown that introducing BIM visualization technology into the stage of building structural design can not only achieve 3D expression of design information, but also promote collaborative work in design, construction, and management, significantly improving the scientific and refined level of building structural design, and providing strong guarantees for quality control in the early stage of construction. BIM technology, with its advantages of visualization, integration, simulation, and collaboration, plays an irreplaceable role in modern high-rise buildings and complex engineering projects. Especially during the construction phase, 4D BIM models combine 3D geometric information with time dimensions to achieve dynamic simulation of construction progress and visual management of the entire process. This model can not only visually present the construction status of each construction stage, but also identify spatial conflicts between structural components in advance through collision detection technology, optimize construction processes, reduce rework and resource waste, thereby effectively improving the safety, precision, and efficiency of construction. Practice has shown that the rational use of BIM technology, combined with customized modeling and management based on actual engineering needs, can help promote the transformation and upgrading of the construction industry towards digitalization and intelligence.

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