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

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Keywords: Building Information Modeling technology; Building structure; Construction simulation; Structural safety

Abstract: Steel structure building has become an important form in modern architectural system. The building structure information model with a certain depth established by building information model (BIM) technology can be used for structural calculation and analysis, structural design, in-depth design of fabricated steel structure, basic model of intelligent construction on site, and maintenance, operation and transformation in the later stage of construction delivery. BIM can integrate the massive heterogeneous data from multiple sources generated in the construction process, and realize the visual, graphical and interactive management of the construction process. In this paper, the construction process simulation and structural safety analysis method of building structure based on BIM technology are studied. By constructing a high-precision three-dimensional BIM model and integrating the time dimension to form a four-dimensional construction simulation, the dynamic visualization of construction progress and procedures is realized. BIM technology must be applied flexibly in the field of building construction, and construction materials should be selected more quickly according to actual needs, so as to achieve the effect that traditional construction methods cannot achieve.

1. Introduction

The wide application of digital and information technology has improved the management efficiency of engineering construction [1]. The construction process is becoming more and more complicated, and the traditional management mode can no longer meet the needs of modern engineering [2]. With the help of visualization methods, key elements such as construction progress, cost control, resource allocation and energy consumption can be dynamically monitored and optimized [3]. The rise of BIM technology provides strong technical support for the digital transformation of the construction industry. When designers apply BIM software to architectural design, they will find that it is very different from the original drawing software applied to design. BIM can integrate and share heterogeneous data from multiple sources in the whole life cycle of a building, and can also build an information platform supporting multi-party collaborative work [4]. All the completed drawings come from the same building model, so all the drawings are interrelated. At the same time, this association interaction is practical, and any changes made to the design in any view can be immediately reflected in the view association.

At all stages of the project, all personnel can insert, extract, update and modify the project information in real time through the BIM platform. This can ensure the accuracy and timeliness of information transmission and realize the efficient cooperation of all parties involved [5]. In the construction stage, BIM technology can combine the 3D geometric model with the construction progress, build a 4D construction simulation system, and realize the dynamic visualization of the construction process [6]. After using BIM technology, the module can be processed quickly and the assembly of multiple parts of the building structure can be completed, which plays a guiding role in practical work and the effect is very obvious. From the reality, the structural design of prefabricated buildings in different areas needs to be improved and adjusted accordingly. This simulation method integrating spatio-temporal information can visually present the operation state of each construction stage [7]. Although BIM technology has great potential in construction simulation, its current application still faces many challenges. Most of the construction scheme simulation systems are low

  DOI: 10.25236/icacel.2025.109

in intelligence, the key construction elements are not clearly expressed, and the simulation results are out of touch with the actual construction [8].

The traditional two-dimensional expressions of CAD are incomplete, especially for some engineering components. Some simple lines are usually used to represent some main parts. In practice, the inclination angle and volume should be considered, and the design intention is often expressed by drawing out labels in the joint design. The dimensions of some components are marked, but other collision problems will occur during actual installation and placement.+

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 is a digital tool that combines modern information technology with traditional construction project management concepts. It is gradually becoming the main driving force for the transformation and upgrading of the construction industry [9]. BIM can simulate construction, thus improving construction efficiency. It is generally believed that in the construction of traditional prefabricated buildings, it is often limited by technical and departmental cooperation and needs to rely on a large number of basic data. BIM enhances the transparency and collaboration of project management, and shows advantages in saving resources, reducing costs, improving efficiency and promoting green and sustainable development. Architectural design is a highly technical job, and each job is very complicated. The application of BIM technology in architectural design is based on three-dimensional technology, which can ensure the coordination between different professional departments and ensure the rationality and stability of development. Its 3D modeling ability enables complex building structures and various components to be visually presented. Designers can use the model to predict and optimize the structural layout, pipeline layout, construction technology and so on.

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 [10]. BIM technology plays an irreplaceable role in the structural design of super high-rise buildings. Facing the super-high-rise project with complex structure, difficult construction and high coordination requirements, the traditional two-dimensional design can no longer meet the development needs of modern architecture. Three-dimensional collaborative design based on BIM improves the design accuracy and expressive ability. Visual design improves the accuracy of design, and stores it as a knowledge base for direct use when encountering the same project, which can greatly improve efficiency and maintain its advanced nature. BIM supports real-time monitoring and feedback in the construction process, and can find and correct potential problems in design or construction in time and optimize the construction scheme. The in-depth application of BIM technology is an important way to promote the intelligent, refined and sustainable development of the construction industry.

2.2 Status and Problems

BIM building model of high-rise assembled steel structure residence is usually built in layers, while BIM structural model is usually built with structural calculation model which is easy to convert and adapt. Although BIM technology is gradually integrated into the construction management process, its practical application still faces practical problems and challenges. 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. Compared with high-rise concrete residence, assembled steel structure building has many types of joints, and joints are the key factors to complete high-rise assembled steel structure residence, involving waterproof, fire prevention, heat insulation and sound insulation. If it is not handled properly, the wallboard may crack due to cold bridges effect, resulting in safety accidents. A lot of manual intervention will increase the workload and reduce the overall work efficiency. Construction engineering involves many professional systems such as architecture, structure, electromechanical, water supply and drainage. Each major is often designed independently, and there is a lack of effective communication and cooperation among designers. This will easily lead to problems such as component size deviation, connection mode mismatch, space collision and so on.

Most BIM modelers are not experienced solution engineers. Their understanding of construction process, key construction nodes and resource allocation logic is not deep enough, which makes it difficult for the BIM model to truly reproduce the on-site construction state in the simulation process. At present, the traditional management mode is still widely used in construction site management, and there is a lack of dynamic fine control mechanism based on BIM. The layout, schedule control and emergency management of the construction site rely heavily on empirical judgment, and the ability to predict unexpected situations is weak. The BIM model lacks real-time data linkage with the actual construction progress, and the model update lags behind, so the simulation results are difficult to effectively guide the field operation.

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:

$$u(t) = f(x, y, z, t) \times n \tag{1}$$

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 4 × 4 homogeneous transformation matrix, which realizes the mathematical correlation between spatial coordinates and time evolution. It is a key mathematical tool that connects the three-dimensional geometric model with the dynamic change of construction progress. Collision detection is mainly used to determine whether there is interference between two or more building structural entities in space under a specific construction sequence. The following formula is used to describe the homogeneous coordinate transformation matrix in the 4D visualization construction model:

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

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

On this basis, Formulas (3) and (4) further describe the space-time state of two different building structure entities in four-dimensional space. When this time and space position match, it indicates that there is a collision.

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

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

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 progress analysis results of the built 4D visual construction model. Through the dynamic simulation of the construction process in time and space, the model can present the execution order, duration and resource input of tasks in each stage. Taking an actual library project as an example, the completion of the proposed 4D model and the traditional 3D BIM technology is compared under the same construction period. The results show that the construction organization based on 4D visualization model is more efficient and reasonable in the complex environment with limited construction space and frequent process crossover. The model can identify process conflicts in advance, optimize construction paths and dynamically adjust resource allocation.

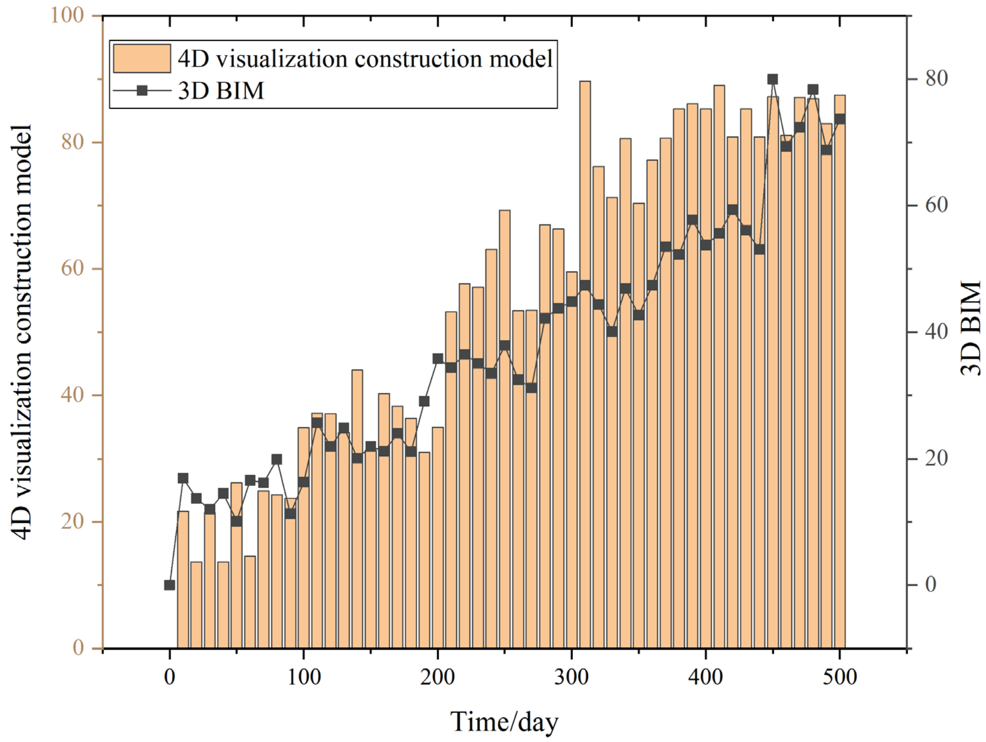

Figure 1 Progress plan analysis

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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