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Optimization of Seismic Performance and Construction Technology of Prefabricated Steel Structures Based on BIM

Yongbin Jia ^{a*}

^a Department of Engineering Management, Shanghai Jian Qiao University, Shanghai 201306, China
*Corresponding author: jyb13059@163.com

Abstract

To address the critical issues of construction and seismic performance in prefabricated steel structure projects, this study leverages a Building Information Modeling cloud platform to seamlessly integrate the four lifecycle stages of design, fabrication, construction, and acceptance. A closed-loop framework integrating seismic performance and construction coordination is developed. Experimental results show that this method significantly improves construction accuracy control. The overall fluctuation of hoisting deviation ranges from 0.28% to 0.35%. The steel column verticality deviation prior to acceptance remains stable at $0.81\% \pm 0.02\%$. The schedule deviation rate over a 60-day construction period is merely $2.1\% \pm 0.2\%$, while the average rectification rate for three major categories of quality defects reaches $99.1\% \pm 0.3\%$. The matching accuracy between the BIM-simulated seismic waveform and the recorded ground motion reaches 99.2%, and the ultimate load capacity of the steel truss reaches 285.6 kN. This approach effectively resolves the challenges of inadequate seismic performance realization and low inter-stage coordination efficiency, substantially enhancing the construction quality, collaborative efficiency, and seismic resilience of prefabricated steel buildings.

Keywords

BIM, Prefabricated buildings, Seismic mitigation, Process optimization

1. Background

Although the annual growth rate of prefabricated steel structure buildings in China exceeds 25%, their application in high-intensity seismic regions (seismic fortification intensity ≥ 8 degrees) accounts for less than 30%. Ensuring seismic performance while synergistically coordinating construction technology serves as a fundamental prerequisite for their widespread adoption in such regions (Wasim & Oliveira, 2022; Bang et al., 2023). In conventional construction practices, three primary bottlenecks compromise the seismic reliability of prefabricated steel structures. First, information fragmentation across project stages leads to significant deviations during the transfer of seismic design requirements, hindering the establishment of a closed-loop collaborative mechanism and causing a disconnect between seismic design intentions and actual on-site structural responses (Soltani et al., 2023). Second, on-site construction quality control relies predominantly on empirical judgment, lacking rigorous quantitative verification of critical parameters such as component fabrication tolerances and hoisting precision, which further undermines the as-built seismic reliability (Takva et al., 2023). Third, the lack of digital support for lifecycle closed-loop management from design to acceptance forms a critical bottleneck that impedes the transition from rapid expansion to high-quality construction (Wang et al., 2024). To overcome these bottlenecks, this study integrates BIM technology throughout the lifecycle of prefabricated steel structures, establishing a synergistic framework that encompasses design, fabrication, construction, and acceptance. The core innovation lies in eliminating inter-stage data silos via BIM technology, embedding seismic quality control gates throughout the lifecycle, and formulating an integrated technical pipeline consisting of information integration, indicator quantification, and closed-loop optimization from initial parameter definition to as-built verification. This study provides an efficient solution for seismic and construction coordination of prefabricated steel structure buildings and is expected to support the development of digital construction theory for prefabricated buildings.

2. Literature review

Seismic resistance in buildings is a core element in ensuring the safety of urban infrastructure and enhancing disaster prevention and mitigation capabilities. It directly governs life safety and structural damage mitigation under seismic excitation, remaining a sustained research focus in structural earthquake engineering. For example, Kontoni et al. (2023) investigated soil-structure interaction in high-rise buildings using a 20-story building benchmarked against configurations of shear walls, braces, and tuned mass dampers. The study clarified seismic optimization indicators but lacked adaptability to different seismic intensities and

physical experiments (Kontoni & Farghaly, 2023). Otieno et al. (2024) addressed the problems of high seismic risk in high-rise buildings and the difficulty of existing methods in accurately reducing dynamic loads that cause structural vulnerability in building seismic resistance. They proposed a framework incorporating smart materials and energy dissipation devices. Experimental results showed that the proposed framework significantly improved building stability and safety (Otieno & Wanjiru, 2024). Wasse et al. (2024) conducted research on concentrically braced frames in building seismic resistance and proposed the integration of artificial intelligence technologies, such as machine learning, to help enhance the resilience of industrial buildings and thereby reduce losses caused by seismic events (Wasse et al., 2024). Arroyo et al. (2025) conducted research on the seismic performance of thin reinforced concrete wall buildings. They established a national seismic risk model and performed nonlinear dynamic analysis. The results provided vulnerability parameters for 4-30 story buildings in low, medium, and high seismic hazard zones (Arroyo et al., 2025).

BIM technology, as a core tool for digital management throughout the building lifecycle, has demonstrated strong technical adaptability in design coordination, construction control, information integration, and other aspects. It has received widespread attention from scholars in related fields and systematic research has been conducted. For example, Michalski et al. (2022) investigated the synergistic benefits of combining lean construction with BIM technology. The study clarified research hotspots such as the benefits of their joint application and issues in synchronous implementation, providing direction for the subsequent development of BIM technology (Michalski et al., 2022). Zhao et al. (2023) explored the acceptance mechanism of BIM technology by analyzing differences among architecture/engineering/construction professionals with different individual characteristics. The results showed that BIM technology characteristics and organizational support have a positive impact on perceived ease of use (Zhao et al., 2023). Zhang (2024) addressed the application of BIM technology in intelligent construction. Through an extensive synthesis of representative engineering projects, relevant literature, and government report analyses, Zhang et al. delineated the functions of BIM in construction quality control, smart project delivery, and facility management (Zhang et al., 2024). Jiang (2023) addressed the deficiency of environmental assessment tools in modern construction by implementing BIM for the whole-life-cycle cost analysis of green buildings. This study basically met the requirements of resource conservation and maintenance, and provided reference for subsequent research (Jiang, 2023). Buronov et al. (2025) applied BIM technology to the measurement of room surface area in architectural design and verified the effectiveness of BIM in the design phase. The results showed that the experimental values had small differences, confirming the effectiveness of BIM technology in the design phase (Buronov et al., 2025).

In summary, existing research in the field of building seismic resistance has formed systematic achievements in material optimization and support frameworks, and the application of BIM technology in digital management throughout the building lifecycle has also become increasingly mature. Therefore, this study focuses on the deep integration of BIM technology with prefabricated steel structure construction and seismic optimization, aiming to construct a full-process collaborative framework. It is expected to provide scientific support for improving the seismic reliability of prefabricated steel structure buildings and promoting the development of digital technology in building seismic resistance.

3. Design of seismic performance and process optimization method based on BIM technology

3.1 Design of seismic performance optimization method

During the seismic performance optimization of prefabricated steel structures, conventional methods rely on static 2D drawings, calculation sheets, and disconnected media for information exchange. Data gaps often lead to excessive deviation rates in the transmission of key seismic parameters, making it difficult to meet the coordination requirements of "parameter-performance-process" in seismic design (Pujari & Momin, 2024). BIM technology achieves full-process information integration through parametric models and controls information transfer deviation within the allowable range. It provides real-time, consistent data support for seismic performance optimization, with its core advantage lying in resolving the fragmentation problem of traditional information management models (Borkowski & Kubrat, 2024). The disparity in information-sharing efficiency between BIM and conventional workflows across the structural lifecycle underpins the proposed methodological framework for seismic optimization. The specific comparison is shown in Fig. 1.

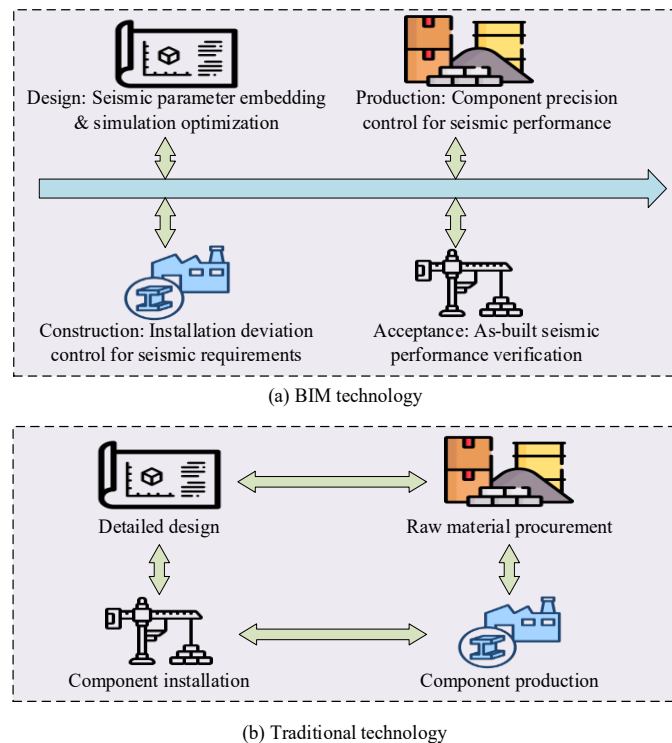


Fig. 1 Comparison between BIM and traditional technology

As shown in Fig. 1, the full construction process of prefabricated steel structures consists of four sequential stages: design, production, construction and acceptance. In the BIM-based workflow, dedicated seismic control nodes are embedded in each stage: seismic parameter embedding and simulation optimization at the design stage, seismic-oriented component precision control at the production stage, installation deviation control for seismic requirements at the construction stage, and as-built seismic performance verification at the acceptance stage. These nodes form a continuous full-chain seismic governance mechanism, with

linear information transmission and real-time cross-stage data feedback, realizing intensive and seamless circulation of key seismic parameters throughout the process. In contrast, traditional technology presents fragmented inter-stage information interaction. Owing to data isolation among project phases, critical seismic parameters, such as joint rotational stiffness and member cross-sectional dimensions, suffer from severe transmission deviations, frequently resulting in on-site rework and the degradation of structural design targets. This fundamental architectural difference indicates that BIM technology can ensure the consistency of "seismic design parameters-component fabrication accuracy-construction installation standards-as-built seismic performance" across the whole process, effectively avoiding the information lag and performance deviation inherent in traditional seismic management. The information transmission deviation rate is calculated as shown in Equation (1).

$$\delta_i = \left| \frac{M_a - M_d}{M_d} \right| \times 100\% \quad (1)$$

In Equation (1), δ_i denotes the information transmission deviation rate, M_a is the actual parameter value received and implemented during the fabrication and construction stages, and M_d represents the nominal seismic design parameter. Based on experimental calibration, the information transmission deviation rate has a linear positive correlation with the member geometric dimension deviation rate, with a correlation coefficient of approximately 0.85; that is, 1% information transmission deviation leads to approximately 0.85% geometric dimension deviation of structural members. This value is a global average for the project, applicable to both primary load-bearing members (steel columns, truss chords) and secondary structural components. Although BIM addresses the deviation problem through information sharing, traditional design modes in the core design stage still suffer from "separation of parametric modeling and seismic indicators, and asynchronous updates between finite element verification and model adjustment." This lack of systematic support hinders the formation of a closed loop from model to verification to correction. To address this, a standardized BIM workflow is developed for the design stage of prefabricated steel structures, with the specific process illustrated in Fig. 2.

As shown in Fig. 2, the standardized BIM workflow at the design stage follows a closed-loop logic of "data-modeling-analysis-collaboration-refinement." First, the "data preparation" phase integrates basic data. Next, the building design model and structural design model are assembled, constructing a BIM parametric model embedded with key seismic parameters. Structural analyses are subsequently executed, and the compliance verification module checks responses against three code-mandated limits in GB 50011-2010 (2016 edition): inter-story drift ratio $\leq 1/500$, joint rotation angle ≤ 0.02 rad, and member stress ratio ≤ 0.85 . Non-compliant items are fed back for parameter optimization using a gradient adjustment method: parameters such as member section size and node stiffness are adjusted proportionally based on the deviation magnitude, with a step size within 5% to ensure convergence. If the judgment passes, equipment models are assembled and collaborative design proceeds. A second judgment follows, after which the component refinement design optimizes section and node parameters, completing the standardized workflow. To quantify inter-story deformation under seismic loads, the inter-story drift angle is calculated as shown in Equation (2) (Ye et al., 2025).

$$\Delta = \frac{\Delta h}{H} \quad (2)$$

In Equation (2), Δ represents the inter-story drift angle, Δh is the inter-story displacement, and H is the story height. To quantify the seismic performance of steel structure nodes, node stiffness is calculated as shown in Equation (3) (Zhang et al., 2024).

$$K_j = \frac{M}{\theta} \quad (3)$$

In Equation (3), K_j represents the joint rotational stiffness (kN·m/rad), M is the applied bending moment at the joint (kN·m), and θ is the relative joint rotation (rad). Engineering design and dynamic seismic response analysis relies predominantly on 2D drawings and engineering empirical rules, which fail to accurately capture critical nonlinear dynamic behaviors such as inter-story drift and joint deformation underground motions (Vaziri et al., 2024). BIM technology, however, simulates seismic oscillations through a three-dimensional information model, dynamically presenting full-process structural responses. Model parameter adjustments update simulation results in real time, allowing designers to optimize seismic performance based on visualized feedback. Therefore, this study constructs a BIM-based seismic oscillation simulation and seismic performance optimization process, as shown in Fig. 3.

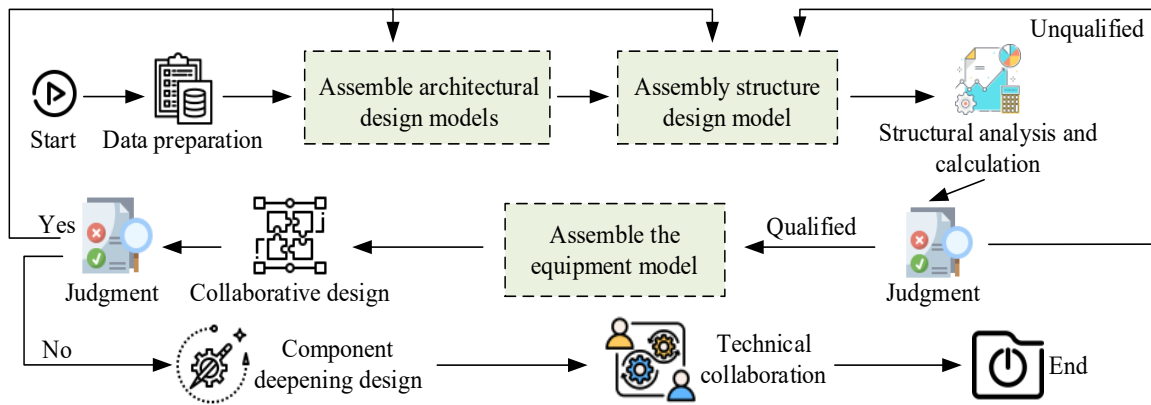


Fig. 2 BIM standardization process diagram

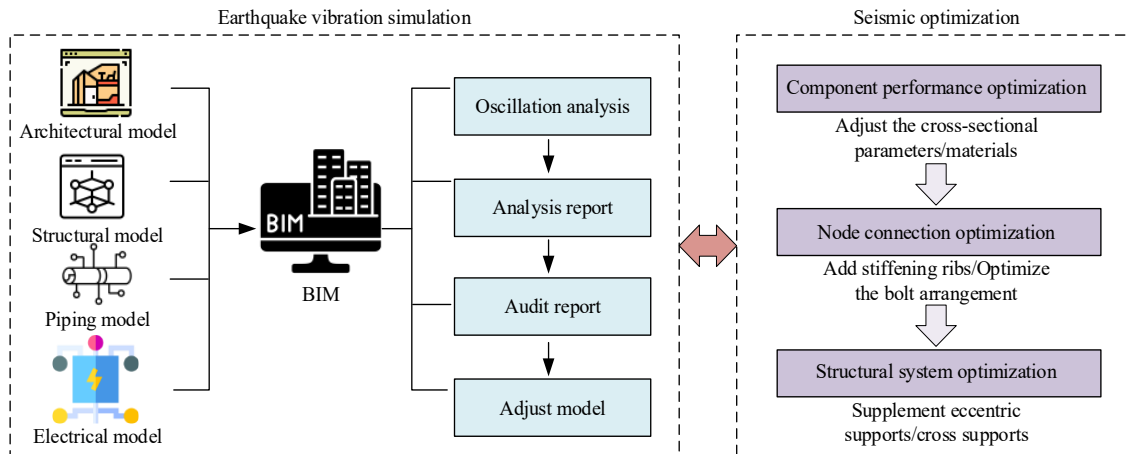


Fig. 3 Oscillation simulation and seismic optimization process

As shown in Fig. 3, the dynamic seismic simulation begins by federating the architectural, structural, and mechanical, electrical, and plumbing (MEP) models into a unified BIM environment. The structural model embeds key seismic parameters, and multi-disciplinary model linkage ensures realistic simulation scenarios. Seismic oscillation analysis is then performed on the BIM model, simulating dynamic responses of the steel structure under seismic loads and quantifying core seismic indicators. The numerical model adopts the following configurations: (a) B31 beam elements for steel members, with tied constraints at beam-column connections. (b) a bilinear kinematic hardening constitutive model for Q355B steel, with a yield strength of 355 MPa, an elastic modulus of 2.06×10^5 MPa, and a Poisson's ratio of 0.3. (c) Rayleigh damping with a 5% damping ratio, and lumped mass distribution at floor nodes. (d) fixed-base boundary condition at the foundation. (e) 0.5 m mesh size, verified by mesh convergence analysis to meet calculation accuracy requirements. The BIM model realizes bidirectional data linkage with the finite element tool through a dedicated interface: parameter modifications in the BIM model are automatically synchronized to the analysis module, and calculation results can be back annotated to the BIM model for visual presentation. An analysis report is generated and audited for compliance to identify weak points. If the audit identifies noncompliance with seismic design requirements, a targeted seismic performance optimization process is initiated. Using BIM's parametric and real-time linkage capabilities, optimization is conducted in three areas. First, component performance is optimized by adjusting section parameters or replacing materials of higher strength for columns and beams exceeding stress limits. Second, joint connections are optimized by stiffener reinforcement or bolt pattern reconfiguration in truss joints exceeding deformation limits, ensuring connection ductility complies with the strong-joint, weak-member design principle. Third, structural system optimization addresses floors with excessive inter-story drift angles by adding eccentric or cross bracing in the BIM model until drift angles are within code limits. The process then re-enters the seismic oscillation analysis loop.

Three core mechanisms account for BIM-driven seismic performance improvement beyond information integration: (1) Full-process parametric consistency control ensures seismic fortification parameters from the design stage are transmitted to production and construction stages without deviation, avoiding attenuation of seismic design intentions. (2) Closed-loop simulation-optimization iteration enables targeted tuning of member sections, connection details and bracing systems based on parametric BIM models. (3) Multi-disciplinary model collaboration eliminates spatial interference between architectural, MEP and structural systems, preventing unintended weakening of seismic load-resisting components.

To quantitatively represent the BIM-enabled collaborative optimization mechanism, the optimization objective is formulated by jointly considering seismic response, fabrication accuracy, and construction installation deviation as shown in Equation (4).

$$J = \omega_1 \frac{R_s}{R_{s,max_2}} \frac{D_f}{D_{f,max_3}} \frac{D_l}{D_{l,max_3}} \quad (4)$$

In Equation (4), J is the multi-objective collaborative optimization function, R_s represents the seismic response deviation, D_f denotes the fabrication deviation, D_l denotes the installation deviation, and $\omega_1, \omega_2, \omega_3$ are the respective weighting coefficients satisfying $\omega_1 + \omega_2 + \omega_3 = 1$. The normalization terms ensure that the three indicators can be jointly evaluated within the same optimization framework. The weighting coefficients are determined jointly by project seismic priority requirements and parameter sensitivity analysis. Based on the BIM-finite element bidirectional linkage, the design parameters are iteratively updated according to the optimization objective as shown in Equation (5).

$$\theta^{k+1} = \theta^k - \eta \nabla_{\theta} J(\theta^k) \quad (5)$$

In Equation (5), $\theta^{k+1} = \theta^k - \eta \nabla_{\theta} J(\theta^k)$ denotes the BIM-controlled design parameters, including member section dimensions and node stiffness, k is the iteration index, and η is the adjustment step size. The updated parameters are synchronized to the finite element analysis model, while the calculated responses are fed back to the BIM model for subsequent evaluation. This formulation explicitly describes the closed-loop mechanism of parameter updating, seismic response evaluation, and cross-stage information feedback.

3.2 Design of production and construction optimization method

At the design stage, the standardized BIM workflow and dynamic seismic simulation generate a prefabricated steel structural scheme that satisfies the seismic design criteria. However, the seismic performance of the scheme ultimately relies on component fabrication accuracy and quality consistency in the production stage. In conventional fabrication workflows, design parameters such as component cross-sectional dimensions and joint weld throat thicknesses frequently experience deviations during data handoff, impairing the actual structural seismic performance. To ensure that design seismic performance is implemented, a full-process quality control system is established through BIM in the production stage, achieving precise conversion from design parameters to physical accuracy. The process is shown in Fig. 4.

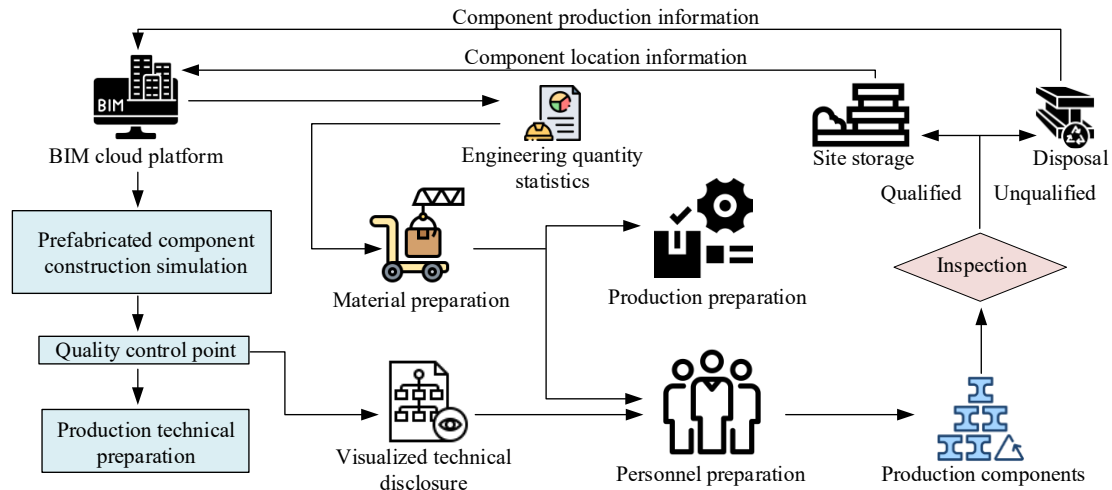


Fig. 4 Specific implementation flow chart of the conversion (Icon source from: <https://iconpark.oceanengine.com/home>)

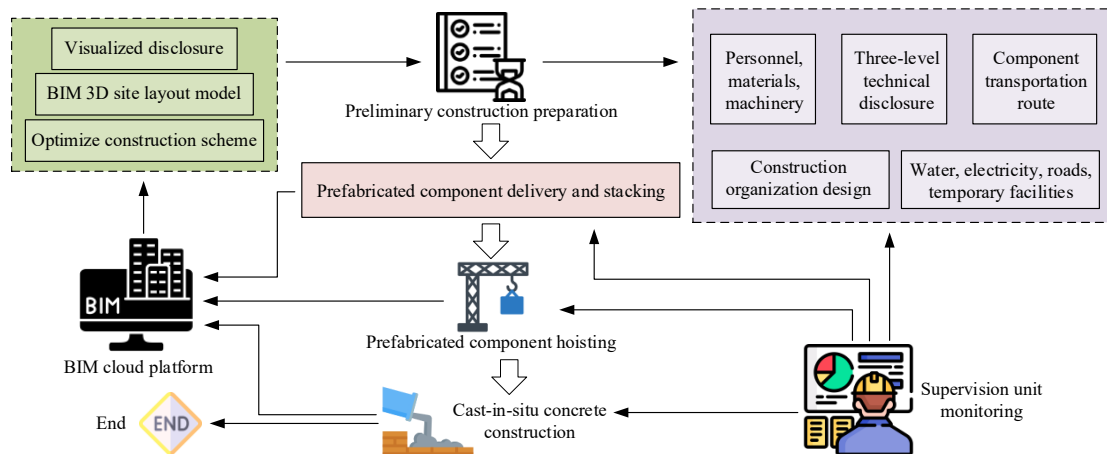


Fig. 5 Full-process quality control system during the assembly and construction phase

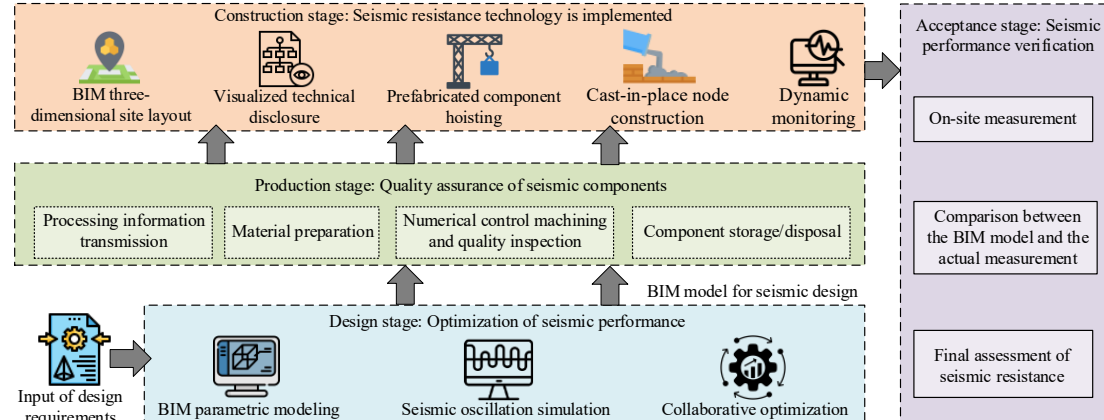


Fig. 6 Coordinated seismic and construction technology for prefabricated steel structures

As shown in Fig. 4, production stage quality control first imports the prefabricated steel structure BIM model from the design stage, extracting production information for key seismic components. Prefabricated component construction simulation is then conducted to identify quality control points in production. Based on simulation results, a quality control point list is generated. Fabrication engineering preparation is subsequently conducted to translate critical quality control checkpoints into executable shop-floor manufacturing plans, concurrently coordinating material takeoffs, shop drawing detailing, 3D visual technical disclosures, and workforce allocation. After completion, the production preparation phase converts BIM processing parameters into CNC machine instructions to drive component fabrication. Produced components enter the inspection phase, where measured parameters are compared with design values using the BIM model to determine compliance. Compliant components proceed to on-site storage, while non-compliant components are processed and feedback is sent to the BIM cloud platform, updating production status. The deviation rate of fabricated seismic components is calculated as shown in Equation (6).

$$\rho = \left| \frac{X_a - X_d}{X_d} \right| \times 100\% \quad (6)$$

In Equation (6), ρ represents component fabrication deviation rate, X_a is the actual fabricated dimension, and X_d is the key seismic component

dimension in the BIM model. Although the fabrication stage ensures dimensional compliance through BIM-based quality management, the lack of rigorous on-site erection control can cause the as-built seismic behavior to deviate significantly from the design target. Traditional construction scheduling relies predominantly on empirical judgment, frequently resulting in joint fit-up misalignments and insufficient structural stability of temporary shoring systems. To achieve the goal of smooth transformation from production accuracy to construction performance, this study develops an overall process quality control system of BIM technology application during the assembling and constructing phase. Its actual implementation process is disclosed in Fig. 5.

As shown in Fig. 5, quality control during the construction and assembly phase utilizes the BIM cloud platform as the core information hub. Through visual instruction, the BIM 3D site model, and the optimized construction planning module, the system translates seismic construction requirements into visual work instructions. Subsequently, pre-construction preparation coordinates resource configuration (personnel, materials, and machinery), a three-tier technical disclosure protocol, and the overall construction organization plan to align seismic demands with available resources. Then, transportation and stacking of prefabricated components follow, where stacking sites are planned based on the component position and seismic connection information from the BIM

model to prevent deformation of components affecting seismic performance. After this is the prefabricated component hoisting phase. Hoisting parameters are established using BIM pre-simulation to inform on-site operations. Cast-in-place concrete operations proceed concurrently in strict accordance with the joint detailing in the BIM model to optimize joint seismic performance. During the entire process, the supervision department monitors and collects real-time construction data and feeds it back to the BIM cloud platform. This workflow achieves full-chain controllability from planning to execution. Hoisting deviation rate is calculated as shown in Equation (7) (Wen, 2025).

$$\eta = \frac{\sqrt{(x_a - x_d)^2 + (y_a - y_d)^2 + (z_a - z_d)^2}}{L} \times 100\% \quad (7)$$

In Equation (7), η represents hoisting deviation rate, (x_d, y_d, z_d) is the designed installation coordinate in the BIM model, (x_a, y_a, z_a) is the actual installation coordinate, and L is the component characteristic length. Combining BIM-standardized seismic performance optimization, production stage quality control, and assembly stage seismic process management, the overall prefabricated steel structure seismic and construction coordination process is constructed based on BIM. It deeply integrates BIM application and seismic control nodes across design, production, construction, and acceptance, as shown in Fig. 6.

As shown in Fig. 6, the BIM-based prefabricated steel structure seismic and construction coordination process uses the BIM cloud platform to connect the four stages of design, production, construction, and acceptance, forming a closed-loop framework for seismic and construction coordination. Using building function and seismic code as input, the design stage completes parametric modeling and seismic oscillation simulation through BIM, producing a seismic design model. The production stage controls component fabrication to ensure deviation rates and material compliance. The construction stage optimizes assembly processes through BIM, controlling hoisting and verticality deviations, while monitoring data are fed back to the platform in real time. The acceptance stage compares BIM models with measured data to verify seismic performance, with compliant results delivered and non-compliant results traced for optimization. This process ensures full-chain information flow, precisely implementing seismic requirements and coordinating construction processes.

4. Construction coordination and seismic performance verification based on BIM technology

4.1 Verification of construction process coordination effect

To verify the performance advantages of the BIM-driven collaborative method for prefabricated steel structure construction technology proposed in this study in terms of precision control, process efficiency, and quality closed-loop management, the study conducted a comparative analysis with three types of commonly used industrial technical methods. These methods included the conventional empirical construction method (relying on 2D drawing disclosures and manual adjustments without digital control), the design-stage BIM application method (single-BIM method, where BIM is confined to design), and the BIM with periodic inspection method (supervision-BIM method). Four methods are set for comparative analysis, with clear differences in implementation scope and technical logic:

1. Experienced construction method: Relies on 2D drawings and manual on-site experience, with no digital process control; seismic requirements are transmitted through paper documents.
2. Single BIM method: BIM parametric modeling is only applied in the design stage; production and construction follow traditional empirical modes, with no digital linkage between stages.
3. Supervision-BIM method: BIM modeling in the design stage periodic third-party quality supervision; data feedback is discontinuous and no real-time closed-loop optimization is formed.
4. Proposed method: Full-process BIM collaboration across design, fabrication, construction, and acceptance, featuring real-time data exchange and closed-loop seismic optimization.

The experiment was based on a 12-story prefabricated steel structure office building project in a certain location (floor height 3.6m, seismic fortification intensity 8 degrees, with Q355B steel columns as core load-bearing components, cross-sectional dimensions 300 mm×300 mm). The complete construction process of 100 steel columns in the project was selected as the test scenario, and the statistical period was set as "from component arrival to completion of all steel column installation acceptance." The experiment collected precision data in real-time through the BIM cloud platform and set precision and efficiency evaluation benchmarks according to the Technical Standard for Prefabricated Steel Structure Buildings (GB/T 51232-2016). Meanwhile, variables such as the technical level of the construction team and component production

batches were controlled to remain consistent to eliminate the interference of irrelevant factors on the comparison results. A total of 100 steel columns were selected and divided into five construction batches (20 columns per batch), and three identical specimens were fabricated for the truss cyclic hysteretic test. All values represent standard deviations at the 95% confidence level, and statistical analyses were performed using Python 3.9. Variables including team size, worker experience and production batch quality are controlled to remain consistent to eliminate interference from irrelevant factors. The specific hardware and software configurations used in the experiment are shown in Table 1.

Table 1. Software and hardware configuration

Category	Core equipment/Software	Simplified model/Version
Hardware	Total station	Leica TS60
	Laser distance meter	Bosch GLM 500
	Graphics workstation	Lenovo ThinkStation
	Cloud server	Dell PowerEdge
	Parametric modeling	Revit 2024.2
Software	BIM modeling	BIM 360 Field module
	Construction accuracy Analysis software	Fuzor 2024
	Data processing tool	Python 3.9
	Progress management	Primavera P6
	Finite element seismic analysis	ETABS 2023
	Seismic response visualization	Fuzor 2024

Based on the above experimental configuration, the study first focused on the collaborative capability of "precision control-process efficiency-problem closed-loop" during the construction stage. From two dimensions of key construction precision indicators and full-process duration and quality rectification, the study compared and verified the effectiveness of the proposed method in construction technology optimization. The results are shown in Fig. 7.

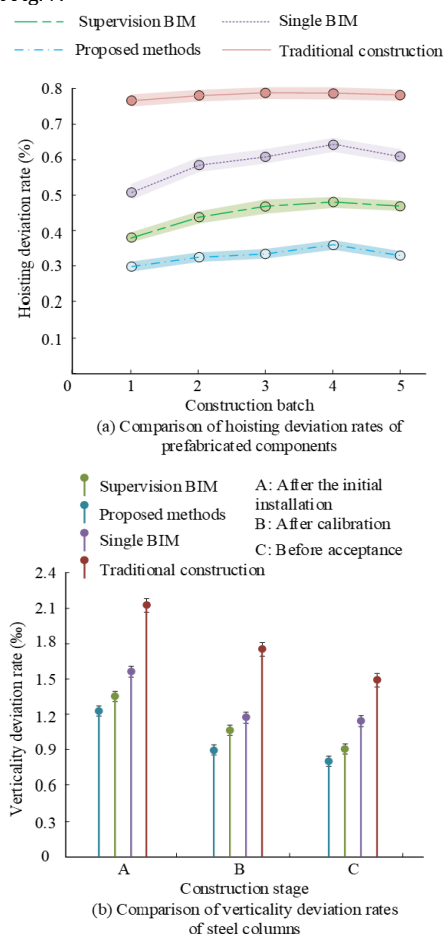


Fig. 7 Comparison of construction process optimization effects

As shown in Fig. 7(a), across successive construction batches, the hoisting deviation rate of the proposed method remained consistently low. Specifically, the deviation was $0.30\% \pm 0.02\%$ in Batch 1 and $0.33\% \pm 0.02\%$ in Batch 4, with an overall fluctuation range controlled within $0.28\% - 0.35\%$, exhibiting a smooth trajectory. In contrast, the hoisting deviation rate of the supervision-BIM method fluctuated between 0.38% and 0.44% , whereas the other two reference methods exhibited markedly higher

hoisting deviations and broader fluctuations. This demonstrated that the proposed method achieved more precise lifting deviation control under different construction conditions. As shown in Fig. 7(b), at three construction stages of after initial installation, after calibration, and before acceptance, the steel column verticality deviation rate of the proposed method was lower. The deviation rate at the initial installation stage was $1.21\% \pm 0.05\%$, after calibration it decreased to $0.89\% \pm 0.03\%$, and before acceptance it stabilized at $0.81\% \pm 0.02\%$, with a deviation reduction magnitude of 33.3%, meeting the regulatory requirement that verticality deviation rate should be less than 1%. To verify the advantages of the BIM-driven construction technology collaborative method proposed in this study in terms of full-process collaborative efficiency, the study compared the performance of the four methods from two core collaborative scenarios: project duration progress control and quality problem rectification. The results are shown on Fig. 8.

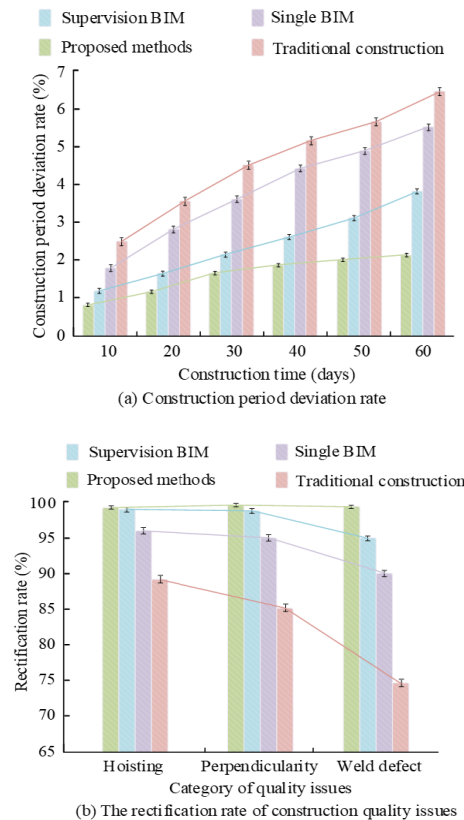


Fig. 8 Comparison of synergy effects in different scenarios

As shown in Fig. 8(a), as construction time progressed, the project duration deviation rate of the proposed method increased most gradually, at $0.8\% \pm 0.1\%$ at 10 days and stabilizing at $2.1\% \pm 0.2\%$ at 60-day acceptance. The traditional empirical construction method had the fastest deviation rate increase, reaching $6.5\% \pm 0.9\%$ in 60 days, approaching the 8% upper limit allowed by industry regulations. As shown in Fig. 8(b), regarding the three categories of quality defects hoisting deviation, column verticality deviation, and weld defects, the proposed method achieved the highest rectification rates across all scenarios: $99.5\% \pm 0.2\%$ for hoisting deviation, $99.4\% \pm 0.3\%$ for verticality deviation, and $98.3\% \pm 0.4\%$ for weld defects. Meanwhile, the rectification rates of the other three mainstream methods (weld defects > verticality > lifting), further highlighting the comprehensiveness and high efficiency advantages of the proposed method in construction quality problem closed-loop management.

The superior performance of the proposed method over the Supervision-BIM method is attributed to three technical factors:

- 1) Real-time closed-loop feedback mechanism, which dynamically adjusts construction parameters, compared with the periodic inspection mode of the Supervision-BIM method.
- 2) Pre-construction simulation prediction, which identifies potential deviation risks in advance and takes preventive measures.
- 3) 3D visual technical disclosure, which reduces human understanding deviation and improves on-site execution accuracy.

4.2 Verification of seismic performance optimization effect

To verify the accuracy of BIM technology in detecting seismic performance of prefabricated steel structures and clarify the degree of agreement between seismic simulation in the design stage and structural response under actual seismic action, this study utilized the aforementioned prefabricated office building and selected the benchmark El Centro ground motion record scaled to a peak ground acceleration (PGA) of 0.2g, corresponding to a seismic fortification intensity of degree 8. By comparing the seismic simulation module of the proposed BIM collaborative method with specific seismic waveform data collected by on-site seismic monitoring equipment (strong motion recorder), focusing on two major dimensions of "seismic waveform fitting degree and structural dynamic response deviation," the study verified the technical advantages of the proposed method in seismic performance detection. The results are shown on Fig. 9.

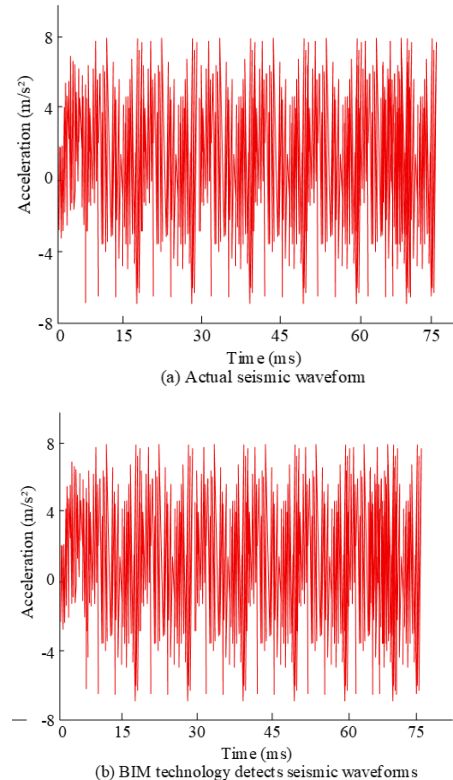


Fig. 9 Comparison of specific ground motion time history data

As shown in Fig. 9(a), the recorded seismic wave exhibited pronounced time-varying amplitude characteristics within the 0–75 ms window, with a peak ground acceleration approaching $\pm 8 \text{ m/s}^2$ and notable dynamic fluctuations. As shown in Fig. 9(b), the BIM-simulated structural seismic response demonstrated excellent agreement with the measured seismic records, capturing virtually identical amplitude variations and phase patterns across corresponding time steps. Especially in the critical vibration segment of 45–60 ms, the waveform peaks, troughs, and change trends of the two reached a consistency of 99.2%, indicating that the BIM-based seismic performance detection method could accurately reproduce the waveform characteristics under actual seismic action. To further verify the optimization effect of the proposed method on the seismic performance of prefabricated steel structures from the dimension of structural component mechanical performance, based on the previous seismic waveform fitting degree analysis, this study selected a typical steel structure truss in the project with the following parameters: 6 m span, 0.8 m truss height. The chords were composed of hot-rolled H-sections (HW150×150), web members utilized equal angles (L80×8), and joints were assembled with Grade 10.9 M20 high-strength bolts; cyclic testing was conducted under displacement-controlled quasi-static loading at 0.5 mm/s, with the specimen weighing approximately 1.2 t. BIM technology does not alter the inherent constitutive properties of steel materials. Its improvement on hysteretic performance originates from full-process quality control: by reducing member fabrication dimension deviation, node installation alignment deviation and initial defect accumulation, the mechanical performance of as-built structures is closer to the ideal design state, resulting in fuller hysteresis loops and higher energy dissipation capacity. Through quasi-static tests, the load-displacement hysteresis curves of the truss under the proposed method, supervision BIM method, single BIM method, and traditional method were compared. The results are shown in Fig. 10.

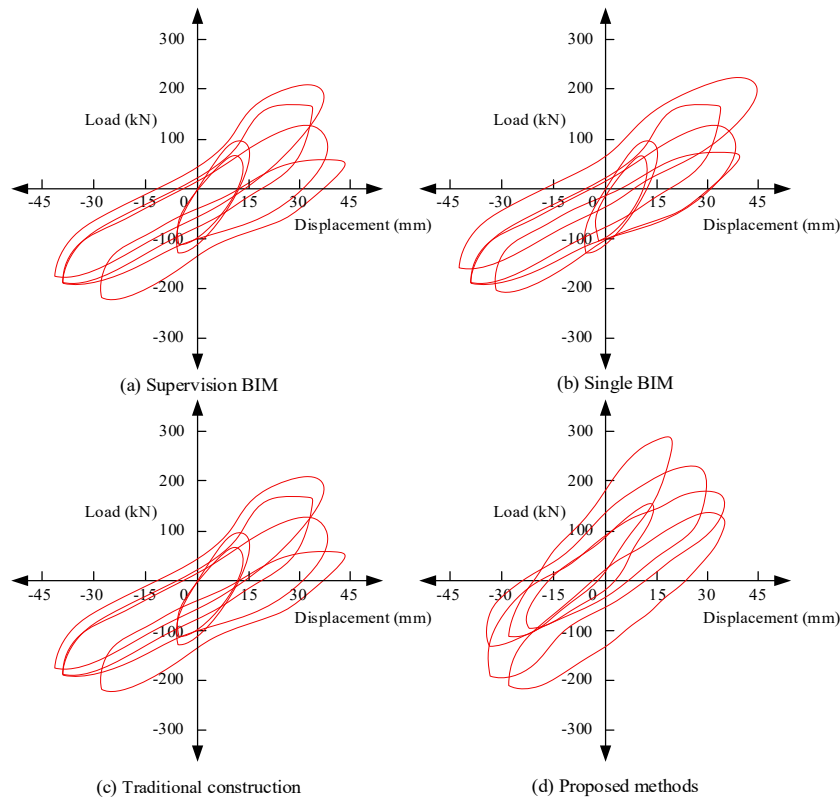


Fig. 10 Comparison of load-displacement hysteresis curves

In Fig. 10(a), 10(b), and 10(c), the hysteresis loops of the supervision BIM method, single BIM method, and traditional empirical construction method were relatively narrow. When displacement reached 30mm, load growth tended to flatten, and the hysteresis loop enclosed area was smaller, reflecting insufficient energy dissipation capacity and ductility. Conversely, as depicted in Fig. 10(d), the hysteretic loops of the proposed method were the fullest, characterized by a higher peak load under identical displacement amplitudes and a considerably larger enclosed area, indicating superior energy dissipation capacity. Meanwhile, the truss under the proposed method could still maintain a high load level after displacement exceeded 15 mm, with better displacement control effect, demonstrating more excellent seismic disaster mitigation performance. In addition, to further analyze the influence of the four methods on the seismic performance of steel structure trusses from the dimensions of strength development and stiffness degradation, based on the energy dissipation and deformation characteristics of the previous hysteresis curves, the study plotted the skeleton curves of the trusses under the four methods. The results are shown on Fig. 11.

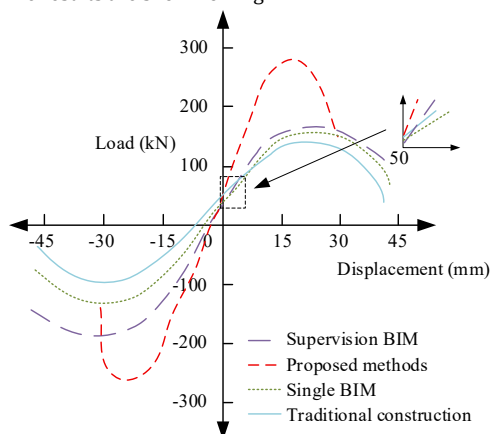


Fig. 11 Comparison of skeleton curves of the lower truss

As shown in Fig. 11, the skeleton curves of steel structure trusses under the four methods intuitively reflected the peak strength and stiffness degradation patterns of the structures. Among these, the proposed method performed best, yielding an ultimate load capacity of 285.6 kN, the highest initial elastic stiffness, and the slowest post-peak degradation rate, maintaining substantial capacity beyond a 30 mm displacement. The supervision BIM method and single BIM method had peak loads and stiffness at intermediate levels. The traditional empirical construction method had the lowest peak load, less than 150 kN, with small initial stiffness and the fastest stiffness degradation in the later stage.

The experimental results showed that through full-process BIM collaboration, the proposed method significantly improved the peak seismic bearing capacity and stiffness stability of the steel structure truss, effectively delayed stiffness degradation, and provided stronger component-level guarantee for the seismic performance of prefabricated steel structures. To further quantitatively evaluate the seismic performance of steel trusses under the four methods from multiple dimensions, four core seismic performance indicators, including ductility coefficient, equivalent viscous damping ratio, residual displacement and inter-story drift ratio, are supplemented for comparison based on the strength and stiffness analysis of skeleton curves. The results are shown in Table 2.

Table 2. Comparison of key seismic performance indicators of steel trusses

Method	Ductility coefficient	Equivalent viscous damping ratio	Residual displacement (mm)	Inter-story drift ratio
Proposed methods	3.82	0.28	2.1	1/515
Supervision-BIM	3.15	0.23	3.4	1/420
Single BIM	2.67	0.20	4.7	1/370
Experienced construction	2.31	0.17	6.5	1/310

As shown in Table 2, the proposed research method performs the best in all seismic indicators. The ductility coefficient reaches 3.82, which is 65.4% higher than that of the experienced construction method, indicating stronger plastic deformation capacity and collapse resistance of the structure. The equivalent viscous damping ratio reached 0.28, reflecting superior hysteretic energy dissipation. Moreover, the residual displacement was merely 2.1 mm, demonstrating superior post-earthquake recentering capability. The inter-story drift ratio is 1/515, which meets the limit requirement of 1/500 specified in the Code for Seismic Design of Buildings (GB 50011-2010) and is significantly better than that of the three comparative methods. All indicators jointly show that full-process BIM collaboration effectively reduces the weakening effect of initial defects on structural seismic performance by precisely controlling component fabrication deviation and installation accuracy, making the seismic performance of the as-built structure closer to the ideal design state.

5. Conclusion

Addressing the problems of difficult construction precision control in prefabricated steel structures, low full-process collaborative efficiency,

disconnection between seismic simulation and reality, and insufficient component bearing capacity, this study proposed a BIM-driven construction technology collaboration and seismic performance optimization method. This method seamlessly integrated lifecycle BIM interoperability, real-time construction sensing, and calibrated dynamic simulations to establish a unified framework bridging construction quality and seismic performance. Experimental results indicated that in terms of construction coordination, the hoisting deviation rate fluctuated within 0.28%–0.35%, column verticality deviation was maintained at $0.81\% \pm 0.02\%$ prior to acceptance, the schedule deviation rate was limited to $2.1\% \pm 0.2\%$, and the average defect rectification rate reached $99.1\% \pm 0.3\%$, effectively overcoming the prominent precision fluctuations and low synergy inherent in conventional methods. Regarding seismic performance, the agreement between the BIM dynamic simulation and the measured seismic response reached 99.2%, while the peak load capacity of the steel truss reached 285.6 kN, demonstrating substantially enhanced component-level bearing capacity and ductility. In summary, this method demonstrated outstanding advantages in construction precision control, full-process collaborative efficiency, and seismic performance optimization, filling the gap of insufficient "construction-seismic resistance" collaboration in traditional technologies. It should be noted that the findings are derived from a 12-story office building scenario, and the optimization weighting coefficients are project-specific, which may require adjustment when applied to other building types or seismic fortification intensities. In the future, the integration and application of this method with digital twin technology will be explored, the artificial intelligence analysis model for real-time monitoring data will be optimized, and its large-scale engineering implementation in super high-rise and large-span prefabricated steel structure projects will be promoted.

Competing Interest

The author declares there's no competing interest.

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Data Availability

Data will be made available at reasonable request.

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