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Methods and Applications of Safety Control for Cable Net Structure Considering Spatiotemporal Changes

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Abstract: The construction of cable net structures is intricate, and the construction process itself is laborious. Conventional safety control measures during the construction of cable net structures involve monitoring cable forces and deformations at specific moments during the construction steps. However, these measures do not guarantee adequate safety assurance. This paper proposes a method for the safety control of cable net structures, considering spatiotemporal changes, based on the concept of digital twins. This method enables real-time monitoring and control of the cable net construction process onsite, facilitating a comparative analysis between the mechanical and geometric information of the construction site and the real-time finite element simulation results. Such an approach ensures safety control throughout the construction process. Firstly, a twin model framework for safety control is established. Then, the methods for spatiotemporal representation, data collection, and processing at the construction site are analyzed. Finally, the proposed method is validated through its application to the Xiaotian Cultural and Sports Park project. The results demonstrate that this method can achieve real-time monitoring and control of cable net structure construction.

Keywords: cable net structure; digital twins; safety control; spatiotemporal changes

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1. Introduction

1.1. Background

As the construction industry continues to evolve, cable net structures are progressively finding applications in expansive venues like sports stadiums. Nevertheless, the intricate structural configuration, diverse array of construction equipment, and complex construction procedures associated with cable net structures present challenges in ensuring safety during onsite construction. Effectively managing safety concerns throughout the construction process has substantial implications for the entire project. In the absence of adequate safety measures, potential outcomes encompass property losses, including material wastage and equipment damage, and can even pose a grave risk to the safety of personnel engaged in onsite construction activities.

Traditional reinforced concrete or steel structures have reached a state of mature development concerning construction safety control, offering a diverse array of safety control techniques or measures. Nonetheless, owing to the necessity of prestressing during the lifting phase of cable net structures, substantial disparities arise between their construction processes and those of conventional structures. Moreover, the construction of cable net structures encompasses extensive deformations and displacements, coupled with numerous component linkages capable of rotation. Consequently, numerous previously established techniques encounter challenges when applied directly to the safety control of cable net structure construction. This underscores the imperative to explore novel approaches for ensuring safety control.

1.2. Literature Review

Cable net structures manifest intricate and varied configurations, wherein distinct construction schemes and procedures wield substantial influence over safety control during the construction phase. Additionally, these structures boast expansive spans, featuring lengthy and weighty cables, accompanied by robust interconnections among diverse components. Consequently, the monitoring of cable net structure construction proves a formidable task, given the challenge of accurately comprehending the mechanical attributes of each constituent at various temporal junctures throughout the construction process. The imperative of ensuring safety monitoring during construction underscores the necessity to investigate an approach capable of real-time construction status monitoring for cable net structures, facilitating concurrent safety control measures.

Ma et al. [1] introduced an analysis and control methodology for hyperbolic paraboloid cable network structures, presenting the mechanical characteristics of the overall structural tensile process. Wang et al. [2] developed a construction error analysis method to investigate the impact of construction errors in load-bearing and stabilizing cables on cable force response. Chen et al. [3] examined the effects of varying tensioning sequences and errors in cable ring connections on the internal forces of cable domes, thereby enabling controlled management of the construction process. Lou et al. [4] utilized a small habitat genetic algorithm to optimize the sequential tensioning of cable net structures, achieving a streamlined construction process and minimizing the total control force required during tensioning. Gao et al. [5] introduced cable net spreading and lifting techniques, integrating finite element analysis with monitoring to ensure the safety and quality of cable net construction. Bai et al. [6] accomplished morphological control of cable net structures by mathematically delineating and analyzing shape optimization, resulting in precise and stable cable net configurations within defined boundary conditions and elastic boundaries. Li et al. [7] formulated a predictive health management system founded on digital twin technology, evaluating the safety condition of the FAST cable net through finite element analysis using the DT model and predicting the fatigue life of cable net components. Jiang et al. [8] proposed an effective approach that merges finite element simulation with a multi-response surface methodology to quantify cable tension uncertainty and evaluate structural reliability. Sim [9] et al. combined wireless smart sensors with vibration-based tension estimation methods to provide an effective method for autonomous long-term monitoring of cable tension. Jo [10] et al. developed a hybrid wireless intelligent sensor network, which improved the sensing ability of the sensor and the data processing algorithm in the network, and applied it to the distributed cable tension monitoring of cable-stayed bridges. Xie [11] et al. proposed a three-layer BP neural network model to predict the cable tension of cable-stayed bridges without installing any acceleration sensors.

From the above research, it can be deduced that the existing safety control approaches for cable net structure construction primarily center around monitoring specific construction step details or analyzing and managing particular facets. Through simulation analysis, simulated mechanical or geometric data from the construction stages are acquired and subsequently juxtaposed with onsite data for analysis. Nonetheless, the real-time nature and comprehensiveness of the monitoring and control processes remain inadequate, giving rise to concerns such as relatively low efficiency, absence of an intuitive presentation, and insufficient precision. In addition, most of the existing research on cable force prediction is still aimed at the cable force of cable-stayed bridges. There are few cable force predictions for cable net structures, and the prediction of cable force changes during the construction of cable net structures is even more lacking.

1.3. Research Significance

The application of digital twin technology in the field of architecture is becoming increasingly widespread, with the ability to synchronize physical information in real space with digital information in virtual space. By analyzing the twin model, various information on the actual construction process can be obtained, thereby achieving construction guidance. Building upon these identified limitations, this paper introduces a new approach to the safety control of cable net structure construction, one that takes into account spatiotemporal variations and is anchored in the concept of digital twins. Employing efficient data transmission techniques and data analysis methods, the objective is to attain real-time monitoring and analysis of the cable net construction process. This, in turn, empowers the achievement of real-time safety control over the cable net construction phase by capturing and analyzing real-time information, encompassing internal forces and deformations of the cable net structure. Through this method, the control accuracy of the measured and predicted comparison of the cable net structure can reach 90%, and the control efficiency is also greatly improved.

The following chapters of this article successively introduce the construction characteristics of cable network structures and the digital twin modeling method for safety control, the characteristics of spatiotemporal changes and data collection and processing methods during the construction process of cable network structures, the application of this method in practical projects, and the conclusion.

2. Consideration of Spatiotemporal Changes in Safety Control of Cable Net Structures

2.1. Characteristics of Cable Net Structure Construction Process

Based on an analysis of the safety control prerequisites during the construction phase, ensuring safety in cable net structures entails a multifaceted mechanical process that amalgamates both temporal and spatial dimensions. Figure 1 shows the construction characteristics of the cable net structure. The specific attributes of this process are outlined as follows:

(1) Construction intricacy: The construction trajectory of cable net structures is intricate, characterized by interwoven relationships between construction equipment, techniques, and material constituents. Adaptations and adjustments prove challenging due to the intricate interdependence. The intricacy of node design, coupled with the construction's inherent difficulty, poses significant challenges. Notably, maintaining the verticality of the lower end of the bracing pole is particularly arduous [12].

(2) Elevated potential energy: Throughout the elevation phase of cable net structures, multiple jacks are employed to achieve simultaneous lifting of tension cables. During this phase, the structure is not fully assembled, resulting in an extremely low overall stiffness that complicates ensuring safety.

(3) Temporal consistency: Across the cable net structure construction journey, stresses within the cables and bracing poles undergo real-time fluctuations. Over time, the mechanical parameters and material properties of components undergo gradual shifts, with these variations influencing safe construction.

(4) Multifactor intricacy: The construction process of cable net structures embraces a multitude of influential elements encompassing construction personnel, machinery and equipment, and the ambient environment. It encompasses the metamorphosis of matter, energy, and information, thereby morphing into a complex mechanism and a vast engineering endeavor.

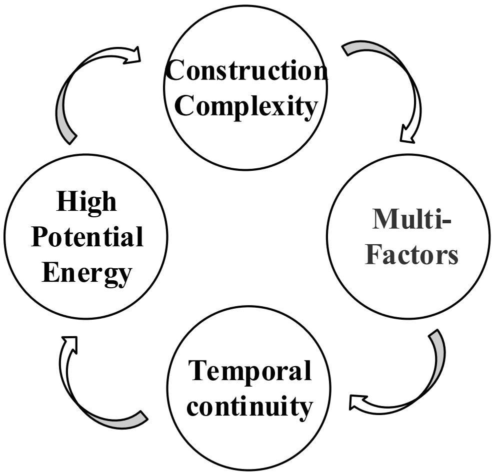


Figure 1. Construction characteristics of cable net structure.

2.2. Establishment Method of Twin Model for Cable Net Structure Safety Control

2.2.1. Principles for Establishing Twin Models

Building upon the attributes of cable net structure construction outlined in the preceding section, there is a compelling need to establish a methodology capable of real-time construction process monitoring, ensuring both safety control and construction quality [13]. In recent years, the concept of digital twins has surfaced and gained momentum, garnering increasing recognition within the realms of architecture and structural engineering. Numerous scholars have embarked on exploring the integration of digital twins in the realm of civil engineering. Current technological advancements and applications encompass quality control within steel structure construction procedures, safety oversight in prefabricated lifting processes, as well as simulation and prognostication of construction sequences. Drawing inspiration from the frameworks of application and model formulation for digital twins evident in other construction domains, this paper introduces a digital twin model tailored for the safety control of cable net structures, all while factoring in spatiotemporal fluctuations [14]. This model stands poised to facilitate real-time monitoring of the cable net structure construction process, thereby steering the course of safety in cable net structure construction endeavors.

Derived from the underpinnings of digital twin technology and the distinct attributes of cable net structure construction, this research advances the formulation of a digital twin safety control model. This model is predicated upon the following foundational principles:

(1) The construction of the digital twin model should be tailored to the demands of cable net structure construction scenarios. While the digital twin model captures the physical attributes of the construction site, it is essential to recognize that not every intricate detail from the site is necessary for the model's efficacy. Consequently, before constructing the model, careful deliberation should be given to the requisites and circumstances of safety control. This approach warrants the establishment of distinct hierarchical and scalable twin models, each fashioned to cater to specific target requirements. As an illustration, the simulation twin model for cable net structure construction and the safety monitoring twin model necessitates distinct modeling methodologies, structures, and data prerequisites.

(2) The digital twin model should seamlessly integrate both temporal and spatial dimensions. Considering the attributes inherent in cable net structure construction processes, the digital twin model must encompass spatiotemporal variations. This integration is imperative to facilitate comprehensive monitoring and control throughout the entire construction journey and for crucial components. Such an approach ensures the precision and thoroughness essential for effective safety control measures.

(3) The digital twin model should excel in real-time information collection, analysis, and feedback. Rooted in the concept of digital twins, this model must attain the capability

to swiftly gather, analyze, and provide feedback on information derived from the physical world. It should effectively monitor the ongoing advancements and diverse parameters of the construction site in real time, subject them to analysis, and furnish constructive guidance to steer the construction process.

(4) Efforts should be directed towards refining the model's scope. Cable net structures frequently encompass considerable scale, and their construction is marked by substantial duration, involving a multitude of components, equipment, processes, and environmental considerations. Nonetheless, for the pursuit of safety control, it is unnecessary to concentrate on all components, equipment, or procedures. Instead, prioritizing the monitoring of pivotal elements suffices. Such an approach serves to curtail the model's extent, thereby mitigating computational analysis duration and subsequent maintenance expenses, all the while guaranteeing astute safety control.

2.2.2. A Twin Model Framework

The safety control of the cable net structure construction process primarily hinges on the acquisition of mechanical parameters and other pertinent data throughout the construction stages. Moreover, the process is also subject to the sway of construction equipment and the surrounding construction environment. The operational condition of equipment and disparities within the environment can exert discernible effects on the cable net structure's evolution during construction. Building on insights garnered from a literature review [15–20] and expert deliberations, the factors that exert influence over the safety control of the cable net structure construction process are visually depicted in Figure 2.

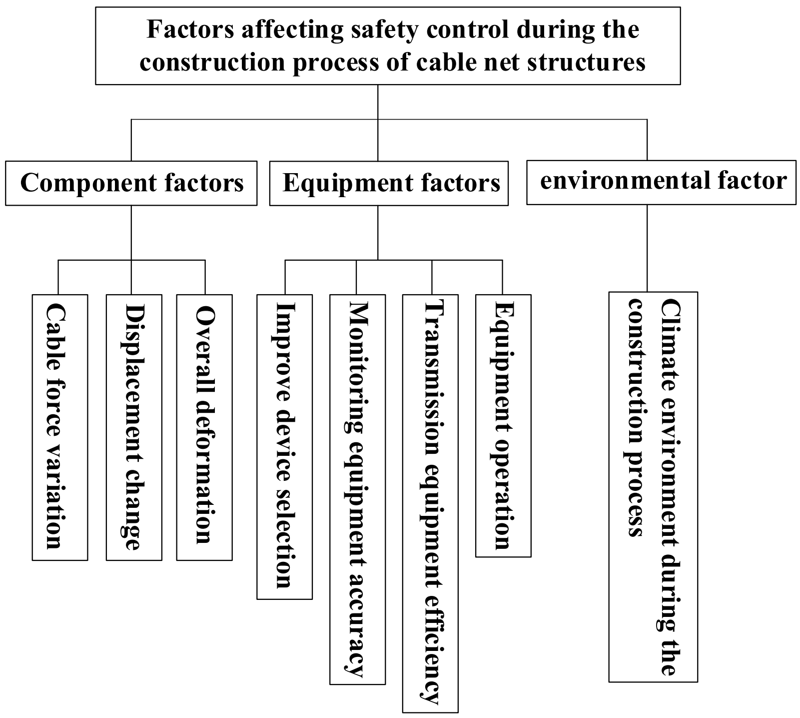


Figure 2. Safety control factors during the construction process of cable net structure.

Building upon the foundational principles of digital twins, a twin model is instituted to govern the safety control of the cable net structure construction process. This model takes into account the intricacies of spatiotemporal fluctuations, complexity, and uncertainty. It operates within the framework of "geometry-physics-behavior-rules" modeling [21].

Initially, the geometric model of the cable net structure construction site is constructed. This encompasses models of construction equipment, structural constituents, and ambient conditions. The logical connections between these components, their functions, and their alterations throughout the construction process are delineated. This methodology ensures the precise accumulation of information from the construction site and facilitates meticulous simulation of the virtual construction progression.

Subsequently, a virtual model is developed, encompassing details about the geometric dimensions and mechanical attributes of the elements, alongside simulation and visualization of the construction sequence. This model stands poised to offer real-time representation of onsite conditions and is equipped for data analysis.

Further, the execution of data collection and transmission takes place. Sensors are deployed at the construction site to capture real-time mechanical data such as stress, displacement, and deformation during the construction trajectory. Wireless networks like 4G, Bluetooth, and WiFi are harnessed to transmit this data to the twin model for analysis.

Ultimately, an analysis and control of safety factors intrinsic to the cable net construction process is undertaken. The data amassed from the construction site are juxtaposed and analyzed against simulation findings. Predicated on the magnitude of discrepancies, a risk classification for the construction process is executed. The BP neural network is incorporated to prognosticate ensuing construction conditions, and the disparity between prognosticated outcomes and simulation analysis findings serves to gauge the safety hazards linked with the construction process. This data-driven support substantiates the safety control of the construction process.

By seamlessly integrating and interconnecting these four components, the safety control of the cable net structure construction process is realized. The delineated process framework is visually illustrated in Figure 3.

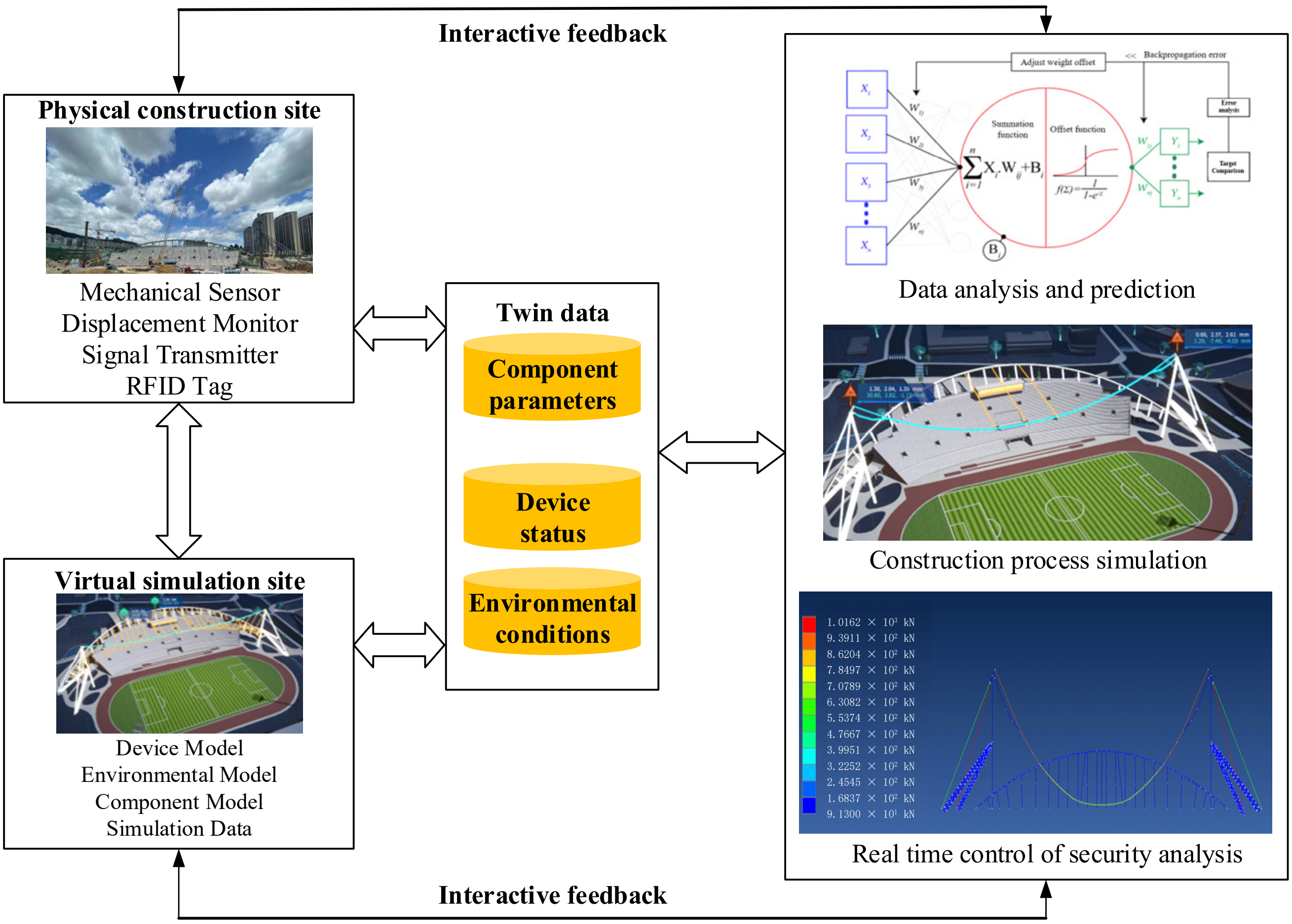


Figure 3. Digital twin framework for the construction process of cable net structure.

3. Modeling Method for Safety Data Mapping Relationship of Cable Net Structure Construction

3.1. Mechanism and Process for Safety Control of Cable Network Structures Considering Spatiotemporal Changes

3.1.1. Characterization of Spatiotemporal Changes

The concept of digital twins inherently embodies spatiotemporal integration characteristics. It pertains to the process of mapping real-world physical entities onto corresponding digital models within a virtual realm. These digital models meticulously mirror the attributes of the physical entities, serving as platforms for data analysis, simulation, prediction, and optimization. In consonance with shifts within the physical entities, the digital twin models also evolve, fostering a two-way exchange of information and iterative refinement. This real-time attribute is referred to as the spatiotemporal essence of digital twins [22]. Elaborate spatiotemporal representation is elucidated in Table 1.

Table 1. Temporal and spatial representation in digital twins.

	Time	Space	Time and Space
Characteristic	Collect past and present data and predict future data, analyze time series through their changes, and predict and maintain physical entities or systems.	Obtain and organize a large amount of data from physical entities or systems and build corresponding models to achieve comprehensive observation, understanding, and analysis of physical entities or systems.	By combining time series analysis and spatial models, data analysis and real-time monitoring can be achieved, thereby achieving comprehensive prediction and optimized control of construction sites or systems.
Data model	The time data model describes the state and behavior of physical entities or systems over time.	The spatial data model includes the composition structure and spatial layout of physical entities or systems, covering geometric, physical, and other information about components and structures.	The spatiotemporal data model endows spatial data with temporal properties, linking time and space, and describing the real-time performance and state of physical entities or systems.
Change characterization	The time cycle can be real-time data based on the construction step level, second level, minute level, hour level, etc., or it can be data that continuously change over time.	The spatial resolution can be micro level, such as component or unit level, or macro level, such as the entire building or engineering, to meet the application needs of different levels.	Search for associated features that exist in physical entities and synchronize them into twin models, such as interactions between objects and mutual influences between features, or relationships between geographic location and weather.

Spatiotemporal data refer to the fusion of time, space, and attributes, representing the fundamental elements that reflect the state and evolution of spatial structural entities. In earlier construction processes, the use of static historical data sequences adequately met the requirements for analyzing the force and deformation aspects of construction elements as structural stiffness gradually formed over time. However, such static historical data no longer meet the demands of modern spatial structures under complex engineering conditions. By defining multiple features and their interactive relationships, connecting various types of sensors and IoT devices to collect real-time data, and establishing the correlation between data and knowledge, the digital twin of a cable net structure can comprehensively control and manage all aspects, from design and construction to operation and maintenance, at different scales. It provides efficient and intelligent management for onsite construction and performs multilevel tasks such as state description, problem diagnosis, process prediction, and decision support.

The spatiotemporal data model inherent in a digital twin framework can gather diverse parameters from both the internal and external dimensions of a physical system, achieved via the integration of sensors and monitors. These collected data can subsequently undergo processing through the application of machine learning, big data analytics, and artificial intelligence methodologies. Using this spatiotemporal data model, the physical system can be subjected to unceasing monitoring, optimization, and real-time maintenance. This dynamic approach allows for nuanced predictions and timely adjustments, thereby bolstering production efficiency and system performance. Importantly, it plays a pivotal role in ensuring the comprehensive safety management of construction endeavors.

3.1.2. Safety Control Process for Cable Network Structures

By amalgamating the risk factors, distinctive attributes, and the framework of the safety control digital twin model for the cable net structure construction process, a precise procedure for ensuring safety during cable net structure construction is put forth:

$$\mathrm{MDS} = (\mathrm{PCS}, \mathrm{CLP}, \mathrm{DLV}, \mathrm{PDM}, \mathrm{CSC}, \mathrm{DAT}) \quad (1)$$

Equation (1) symbolizes the digital twin model (MDS) engineered for the safety control of cable network structure construction, encapsulating the dynamic influences of temporal and spatial shifts. In this context, the following notations hold significance:

PCS: Denotes the physical construction site of the cable network.
CLP: Represents the lifting and tensioning progression of the cable network.
DLV: Stands for the virtual model designated for lifting and tensioning.
PDM: Corresponds to the comprehensive big data storage and management platform.
CSC: Signifies the dedicated cable network construction safety control service.
DAT: Encompasses the data collection and transmission processes, fostering seamless exchange between the lifting process, virtual model, extensive big data management platform, and the specialized cable network construction safety control service.

Drawing upon the foundations of digital twins and harnessing the capabilities of IoT technology, this approach hinges on real-time data collection facilitated by onsite acquisition devices. Following data collection, the gathered information is transmitted to a cloud-based data collection system using a TCP connection across a 4G network. Subsequently, the data collection system dissects the data and forwards it to the backend system. Within the backend system, the data undergo analysis, processing, and storage. The results of computed analyses and control directives for ensuing construction procedures are communicated through the utilization of message queuing telemetry transport (MQTT). These transmissions culminate in the display of information on a web page, enabling managerial personnel to attain real-time monitoring and oversight of the construction site. With Equation (1) serving as a foundation, the process for safety control during cable network structure construction, mindful of temporal and spatial fluctuations, finds visualization in Figure 4.

Initially, an array of data sensors, coupled with corresponding collection and transmission devices, is strategically positioned at the physical construction site. This installation aims to capture safety control data pertinent to the cable network's lifting and tensioning stages. The gathered data undergo transmission to the expansive big data storage management platform, which serves the dual purpose of collection and storage. The platform proceeds to employ algorithms to conduct a comprehensive analysis of the data, thus propelling the safety control mechanisms associated with the lifting and tensioning activities. Ultimately, the outcomes stemming from the safety control endeavors within the lifting and tensioning phases are transformed into a visual format via the employment of the virtual model. This visualization engenders an accurate and lucid representation. Consequent decisions and responses stemming from the control system are subsequently operationalized through the intervention of actuators and controllers throughout the in situ cable network lifting and tensioning process.

Using the mentioned process, a dynamic loop of real-time interaction and reciprocal feedback materializes between the cable network's onsite lifting and tensioning progression and the corresponding virtual model. This dynamic interplay facilitates the provisioning of service functionalities devoted to the safety control of cable network structures, effectively accommodating the influences of temporal and spatial fluctuations.

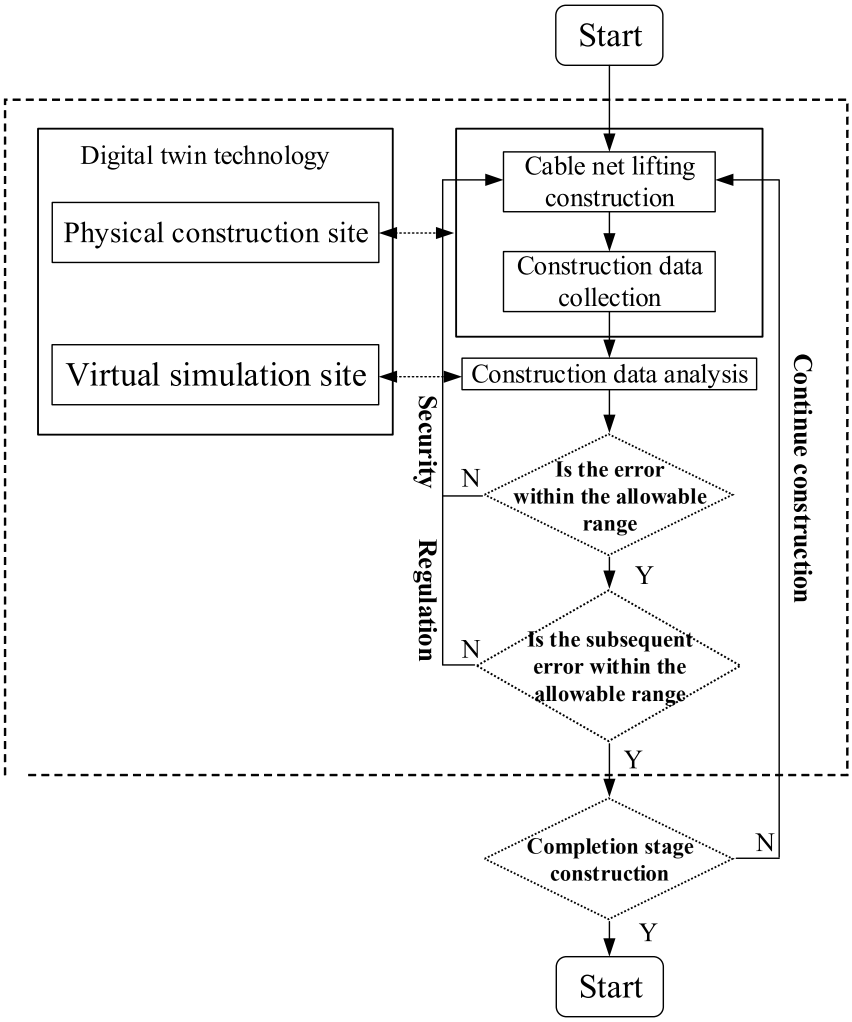


Figure 4. Safety control process of cable net structure.

3.2. Data Processing for Safety Control of Cable Net Structures

3.2.1. Onsite Monitoring Data

To warrant the security of the construction process and to grasp the intricacies of structural deformations and fluctuations, the incorporation of onsite construction monitoring emerges as a prerequisite. By integrating real-time monitoring throughout the construction journey, precise safety control and guidance can be achieved, as underscored in the existing literature [23]. Facilitating seamless real-time monitoring and control of the construction process necessitates the fulfillment of several prerequisites:

First and foremost, there is an imperative to procure real-time insights regarding the construction site. This entails garnering information encompassing the tautness of cable networks, the displacement of structural constituents during the construction process, and the prevailing environmental conditions at the construction site.

Subsequently, the amassed onsite information mandates swift and comprehensive analysis and processing. This analytical endeavor encompasses the evaluation of the prevailing safety state of the cable network structure and the anticipation of safety parameters underpinning forthcoming construction phases.

Lastly, the expeditious transmission of data and control outcomes is crucial to ensure the instantaneous availability of monitoring data and the timeliness of safety control interventions. This, in turn, cements the efficacy of monitoring data and the celerity of safety control protocols, collectively fostering a proactive approach to safety assurance.

Construction process monitoring can be divided into two main parts [24]: geometric monitoring and physical–mechanical monitoring of the structure. These can be further categorized into three aspects [25–27]:

(1) Cable tension monitoring: Cable tension monitoring holds paramount significance in the pursuit of shaping the structure as intended. Consequently, vigilant oversight of cable tension throughout the cable tensioning process stands as an imperative requisite.
(2) Structural deformation monitoring: Structural deformation monitoring assumes a pivotal role in the assessment of overall deformation patterns within the structure. It stands as a pivotal criterion in ascertaining whether the structure aligns with the prescribed design specifications.
(3) Structural displacement monitoring: Monitoring the displacement of the structure furnishes a vantage point into the evolution of the construction endeavor. Such information finds utility in establishing correlations with corresponding finite element models, a practice integral to conducting safety analyses of the structure at specific junctures.

Based on the safety control requirements, the following demands are proposed regarding data monitoring:

(1) The monitoring plan should be designed to accurately reflect the dynamic changes in the structure and its surrounding environment. Real-time monitoring and simulation predictions should be employed as the basis for the monitoring scheme.
(2) The monitoring duration should be initiated from the preconstruction phase of the cable network structure and should persist until the culmination of the tensioning process.
(3) Each monitoring parameter must undergo uninterrupted real-time monitoring throughout the entirety of the construction process. Even during intervals when construction operations are temporarily suspended due to procedural considerations, vigilance over all parameters must persist to ensure the unbroken continuum of monitoring data.

3.2.2. Twin Simulation Analysis

A digital twin model, harmoniously melding technologies like virtual modeling and finite element software, is harnessed to replicate the entirety of the construction process taking place on the construction site. This simulation endeavors to furnish insights into the fluctuations of cable tension, cable network deformations, and displacements at pivotal nodes. This comprehensive portrayal encompasses the span from construction preparation to the culmination of tensioning activities [28]. This process unfolds through the ensuing steps:

Primarily, the building information modeling (BIM) technique is leveraged to establish the intrinsic details of components and the overarching framework of the cable network structure. This encompasses a spectrum of attributes such as geometric dimensions, material properties, and assorted physical characteristics affiliated with the components.

Subsequently, the virtual model undergoes integration into finite element analysis software, thereby orchestrating the emulation of the cable network structure's construction process. The outcomes of this simulation—spanning fluctuations in cable tension, displacements, and deformations—are meticulously archived within a comprehensive big data management platform. This repository furnishes real-time accessibility, fostering subsequent data analyses.

Ultimately, employing sensitivity analysis affords insights into the repercussions of diverse construction discrepancies upon the resulting structure. Sensitivity analysis is instrumental in pinpointing areas of heightened sensitivity, paving the way for the subsequent execution of error analysis. The latter serves as a conduit for the establishment of error thresholds. These precision-oriented data management strategies are enacted during the engineering construction phase and subsequently extended to predictive control protocols.

By harnessing the virtual model of the structure and conducting meticulous construction simulation calculations, the viability of the tensioning construction plan is meticulously validated. This validation process stands as a robust assurance mechanism, safeguarding the safety of the ensuing tensioning and forming activities.

The continuum of changes in cable tension experienced during the lifting process is meticulously captured. This dataset serves as the bedrock for determining the practical tensioning force and subsequent monitoring of cable tension. Similarly, insights into the displacement patterns exhibited by the structure during the tensioning process are garnered. This trove of displacement data serves as a theoretical foundation for monitoring displacement during tensioning operations.

Through a methodical comparison between onsite measurement data and simulated data, the safety performance and construction quality of the structure throughout its construction journey can be effectively assessed. This evaluative endeavor subsequently informs onsite construction activities based on the outcomes of the analysis.

Drawing from the repository of construction experience, it is evident that during the initial phases of the cable network structure's lifting and tensioning process, the variation in cable tension tends to be more pronounced due to the structure not yet attaining full form. Consequently, during these preliminary stages of construction, safety control hinges on the meticulous monitoring of the structure's displacement and deformations, ensuring their adherence to acceptable error margins. Conversely, as the structure matures and attains a higher level of stability in the later stages, safety control pivots to cable tension monitoring, guaranteeing both the safety and quality of the construction enterprise.

3.2.3. Safety Control

(1) Establishment of BP neural network

Conventional mathematical modeling approaches confront inherent limitations when it comes to realizing precise predictive outcomes for nonlinear processes, particularly the lifting of cable network structures. Conversely, the artificial neural network (ANN), a widely embraced mathematical modeling technique, underscores its prowess in accommodating extensive datasets [29,30]. By assimilating insights from historical data, the ANN adeptly discerns the intricate mapping relationship that underpins input–output data. The learning phase extracts this mapping association, and subsequently, during the prediction phase, the forthcoming cycle's output can be extrapolated based on the input data harnessed by the network. Visualized in Figure 5, the structure and mathematical depiction of the backpropagation (BP) artificial neuron (hidden neuron) is indicated. When confronted with uncertainties, the resourcefulness of large-scale sample learning can be harnessed to mitigate the margin of error in state evaluation and culminate in meticulous outcomes.

Neural networks boast a distinctive array of advantages spanning data storage, organization, and generalization. In addition, BP neural networks have been widely used in the field of construction, such as quality control and structural health monitoring. They can predict potential structural problems such as cracks and deformations and have high accuracy and efficiency. This multifaceted prowess positions artificial neural networks (ANNs) as a salient technical avenue within the realm of data prediction systems tailored to ensure safety control amid the construction journey of cable network structures. Their pragmatic utility is underscored by their robust potential.

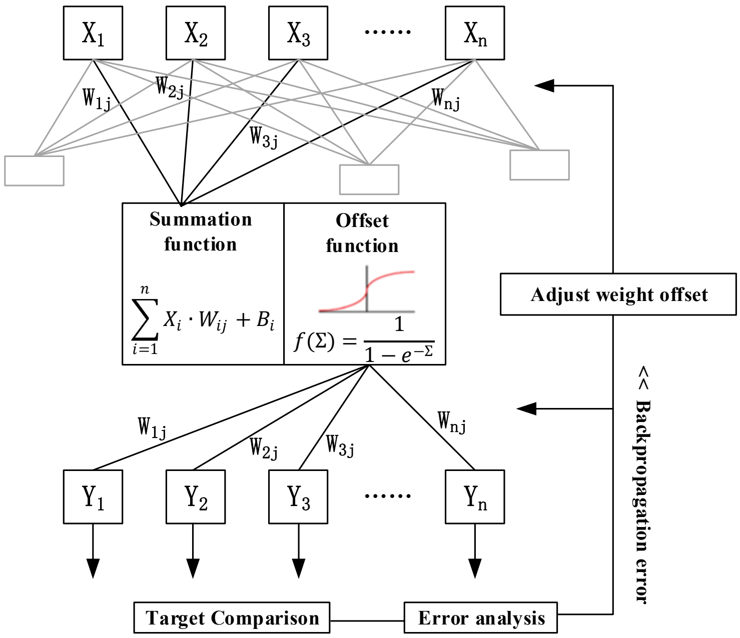


Figure 5. Structure and mathematical representation of BP artificial neurons (hidden neurons).

The present quandary centers on prognosticating the forthcoming structural shifts that unfold during the ensuing construction phases, predicated upon the prevailing state of the cable network structure amid the lifting process. Consequently, the input vector encompasses a constellation of current coordinates (X, Y, Z) about diverse components, the magnitudes of cable forces (measured in kN), and the intricate cable network configuration. Contrarily, the output vector encompasses the coordinates (X, Y, Z) and cable forces (expressed in kN) projected at a prospective time juncture, complemented by the envisaged cable network configuration.

To improve the accuracy of the neural network, a large amount of data is required for training, validation, and testing. Therefore, finite element analysis of several specimens undergoing cable network lifting was conducted using ANSYS. Firstly, collect the data of finite element analysis and the construction data of similar structures before, clean the data, deal with missing values and outliers, and ensure the quality and consistency of the data. The data set is divided into a training set, verification set, and test set according to the ratio of 7:2:1, and the neural network prediction model is trained, verified, and evaluated until it meets the accuracy requirements. The measured data of the construction site are collected by various sensors and imported into the twin model to compare with the simulation results of the finite element model. According to the error value, the neural network is used to predict the mechanical characteristics of the subsequent structure. The working flowchart of the prediction algorithm is shown in Figure 6.

(2) Analysis Control

Harnessing ANN for the regulation of construction safety in cable network structures encompasses the classification of warning levels predicated upon specific benchmarks. The precise classification criteria are delineated in Table 2. To enhance the clarity of presentation, this study demarcates the warning levels into four distinct tiers: normal, blue alert, orange alert, and red alert.

To guarantee the safety and stability of the construction process, predefined precautionary thresholds were established. The warning limits for structural deformation at every construction phase should not surpass 20% of the theoretically computed values. Similarly, the warning thresholds for cable tension during each construction stage should remain within 10% of the theoretically calculated values.

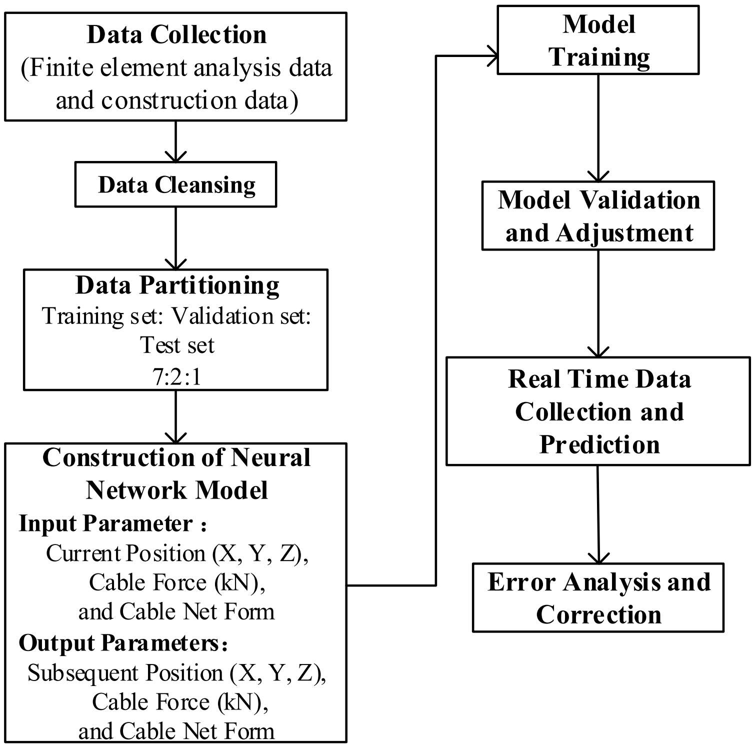


Figure 6. Flowchart of prediction algorithm.

Table 2. Classification of safety hierarchy of hazard controls.

	Cable Force Deviation	Deformation Deviation	Prediction Deviation
Normal	<1.02× Simulation value	<1.05× Simulation value	<1.1× Simulation value
Blue alert	<1.05× Simulation value	<1.07× Simulation value	<1.2× Simulation value
Orange alert	<1.07× Simulation value	<1.1× Simulation value	<1.3× Simulation value
Red alert	<1.1× Simulation value	<1.2× Simulation value	<1.5× Simulation value

The specific analysis process is as follows:

Initially, displacement sensors stationed at the construction site facilitate the acquisition of precise positional data throughout the cable network lifting phase. These data furnish insights into the real-time progress of the endeavor. Concurrently, tension sensors and deformation sensors procure dynamic data about the tension and morphological shifts of the cable network. These three data streams are conveyed in real-time to the digital twin analysis model, wherein they undergo comparative and analytical evaluation regarding tension and deformation.

Subsequently, predicated on the position data, the prevailing condition of the structure at the construction site is aligned with the structural simulation analysis furnished by the digital twin model. The disparity between the current state's tension and deformation and the digital twin's simulated data is scrutinized. Leveraging this discrepancy, the safety tier of the present structural state can be ascertained. If the discrepancy falls within the permissible range, the simulated tension values and morphological data, corresponding to that construction juncture, are reconciled with the actual onsite observations.

Leveraging artificial neural networks (ANNs), the ensuing construction process's tension and deformation are scrutinized and contrasted with the simulated values. Hinging on the extent of discrepancy, the safety status of the upcoming construction endeavor is delineated across the four previously mentioned gradations: normal, blue alert, orange alert, and red alert. Should the structure align with the normal tier, the construction proceeds as planned. In instances of a blue alert, equipment operation warrants verification. Upon encountering an orange alert, a thorough evaluation of equipment conditions and the mechanical performance of pivotal components is imperative. Should a red alert materialize, construction must be promptly suspended, and a recalibration of the construction strategy is in order [19].

4. Case Study

The Xiadian Sports Park is situated at the juncture of Longzhong Road and Huancheng South Road, within Dehua County, Quanzhou City. Functioning as a Grade C sports stadium, it encompasses a total construction expanse spanning 14,690 square meters. The stadium configuration encompasses a concrete frame structure grandstand, accompanied by a single-layer cable net roof, along with supplementary amenities. Notably, the grandstand attains a maximum elevation of 21 m, whereas the roof reaches its zenith at 50 m above ground level.

The roofing design for this project incorporates a single-layer cable net roof configuration, characterized by one rigid boundary and three flexible linear boundaries. Spanning an impressive 215 m by 54 m, the roof encompasses crescent-shaped steel ring beams and steel diagonal columns that function as boundary components. Within this arrangement, load-bearing cables are thoughtfully arranged in a concave layout, while stabilizing cables adopt a convex configuration, ultimately culminating in the formation of the single-layer cable net roof. This intricate system involves the connection of cables to the mast via ring cables and edge cables, complemented by the installation of back cables to ensure equilibrium. Figure 7 provides a comprehensive three-dimensional representation of the structure, while the force transmission pathway of the cable arrangement is depicted in Figure 8.

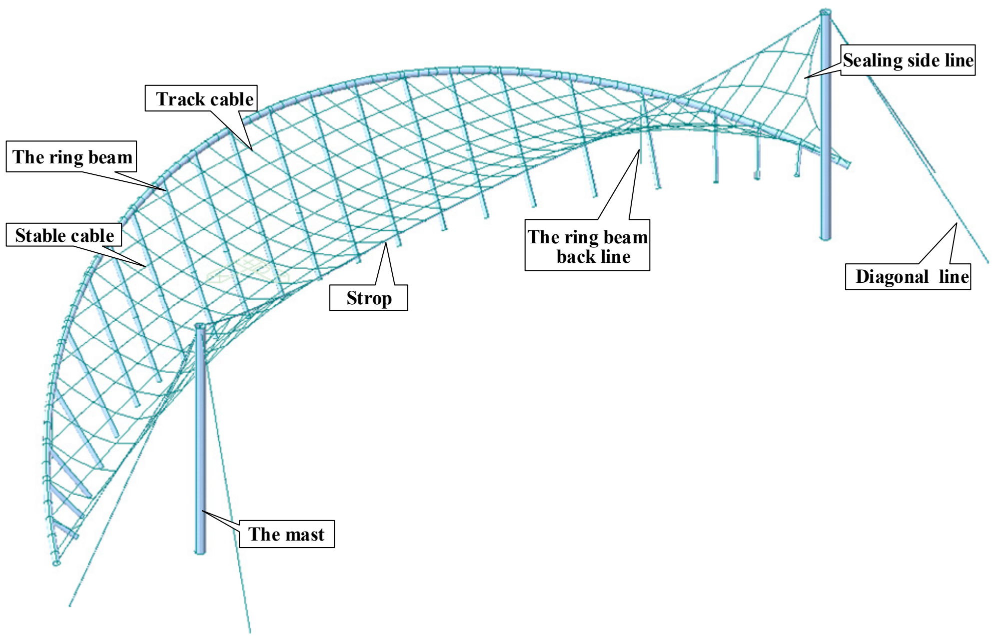


Figure 7. Three-dimensional structure diagram.

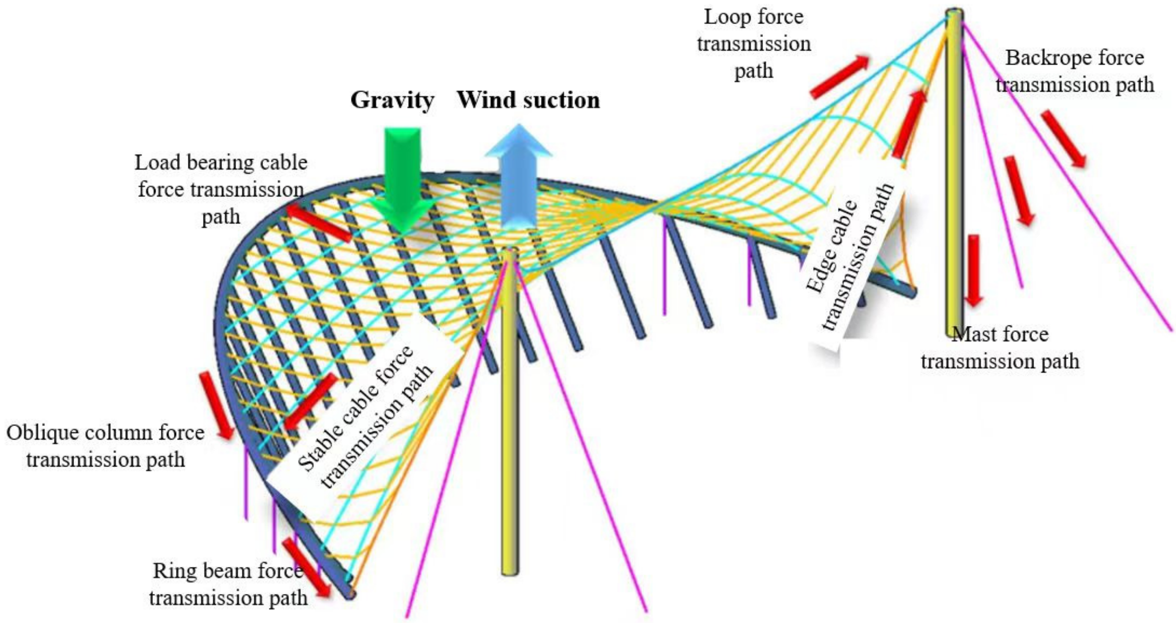


Figure 8. Cable structure force transmission path.

4.1. Establishment of Onsite Twinning Model

1. Spatial Dimension Modeling

The spatial dimension comprises both physical and virtual realms. Modeling the physical space entails collecting data concerning the positions and statuses of components, equipment, and personnel. To enhance monitoring and gather component-specific details, RFID tags can be embedded within cables or other components. These tags store unique identification IDs and fundamental attributes, enabling accurate tracking of component locations and mechanical information, and facilitating tailored control adjustments for specific components throughout the construction phase.

On the other hand, the virtual space necessitates the incorporation of the building's 3D model, finite element model, and diverse component information. This virtual space retains simulated cable forces and displacements during the cable network's lifting and tensioning processes, thereby serving as a basis for cable analysis and facilitating safety control measures during the construction stage.

2. Time Dimension Twinning

Real-time data collection of cable forces and displacements through sensors positioned on the construction site is transmitted to the twin model. The twin model incorporates cable force and displacement data obtained from finite element analysis of the cable lifting process [31]. By aligning the cable network's condition on the construction site with the finite element analysis of the cable network, based on the gathered cable network positions, the cable forces and deformations under that particular state are assessed. This facilitates real-time control within the temporal dimension. Furthermore, leveraging an artificial neural network (ANN), the twin model can forecast cable forces and deformations for future time points, ensuring the construction process maintains a secure state.

3. Virtual Reality Interaction

To enable interaction between the physical model at the construction site, the virtual model of the digital twin, and the twin data, a robust and low-latency data transmission protocol is employed. Data transmission methods including 4G, Wi-Fi, and Bluetooth are utilized to establish seamless connections among these elements. This ensures both hardware and software support for efficient data transmission.

In the context of cable network lifting, the twin data model primarily serves the purpose of construction safety control. Onsite, cable force information is collected using hydraulic pressure sensors, while position information for monitoring points is acquired through GNSS or BeiDou satellite navigation systems to ascertain the construction status of the cable network. These collected data are transmitted to the digital twin virtual model through a 4G network using TCP communication. Subsequently, the data are compared with the cable force and displacement information obtained from finite element analysis. Based on the extent of the error, control guidance is provided to the construction site.

4.2. The Realization of Security Control

4.2.1. Device Selection

The selection of the lifting pump and hydraulic jacks within the lifting equipment is based on the ultimate lifting force requirements. Initial calculations indicate that a 60-ton hydraulic jack be employed for the primary lifting of the main cables, complemented by the ZB500 hydraulic pump. For the inclined cables and loop cables, 250-ton hydraulic jacks are utilized in conjunction with the ZB800 hydraulic pump.

For monitoring the tension of the steel cables, hydraulic pressure sensors are employed to ensure that the stress during the construction process of prestressed cables aligns with the design unit's requirements. The measurement principle is as follows: Throughout the tensioning process, the hydraulic pressure generated by the hydraulic pump is measured using the hydraulic pressure sensor and subsequently converted into force. The cable force value is read using an electronic reading instrument, as shown in Figure 9.

Figure 9. The oil pump and supporting oil pressure sensor.

An integrated universal receiver, illustrated in Figure 10, is installed at the construction site. This receiver is endowed with a range of functionalities, including surface displacement monitoring, deformation monitoring, and applications involving differential reference stations. It is compatible with various satellite navigation systems and frequencies, encompassing BDS, GPS, QZSS, and GLONASS, among others. Furthermore, it supports a dual-frequency RTK algorithm, guaranteeing consistent provision of high-quality raw observation output and high-precision positioning services at millimeter-level accuracy. Furnished with a built-in GNSS/4G/Wi-Fi integrated antenna, it also features embedded temperature and humidity sensors along with MEMS sensors. The receiver facilitates the amalgamation of acceleration, tilt, and GNSS monitoring, rendering it a proficient millimeter-level positioning receiver.

With the utilization of this device, the collection of displacement and deformation information during the cable net lifting process becomes feasible. Several pivotal locations within the cable net structure are designated to monitor displacement and deformation. This enables an accurate assessment of the advancement of construction activities at the site. The arrangement of measurement points onsite within the cable net structure is depicted in Figure 11 [32–35].

Figure 10. Schematic diagram of an integrated universal receiver.

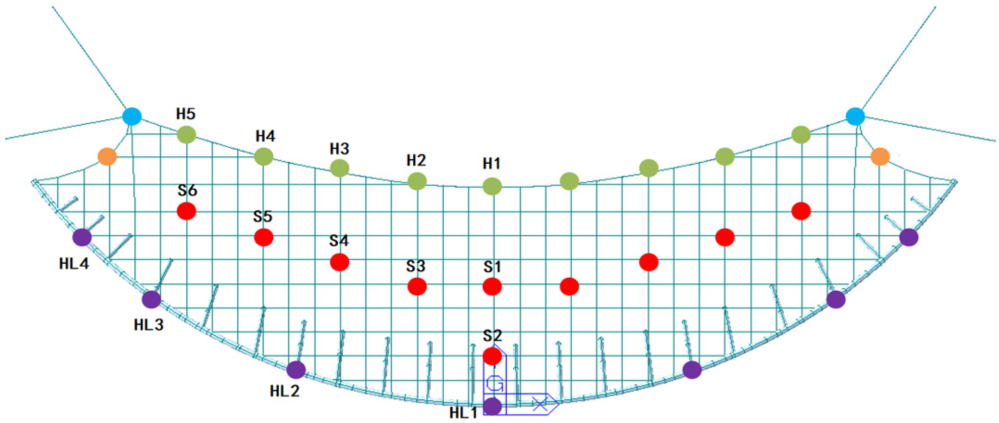


Figure 11. Layout of measurement points.

4.2.2. Control Flow

Control principles are as follows:

(1) The tensioning process constitutes the utmost pivotal stage in the construction of cable net structures. If the measured tension significantly deviates by more than 10% from the anticipated outcomes obtained through simulation calculations, an immediate suspension of the tensioning process is warranted. Subsequently, upon ascertaining the underlying cause, the prestressing procedure can be recommenced.

(2) Should the structural deformation surpass a threshold of 20% in comparison to the design calculations, an immediate cessation of the lifting process becomes imperative. After the identification of the root cause and the implementation of appropriate remedial measures, prestressing can be resumed.

(3) Given the sensitivity of the displacement at the top of the mast to alterations in cable tension, it is advisable to conduct the tensioning process continuously and gradually.

By performing construction simulation calculations, it is recommended that the horizontal displacement at the top of the mast does not exceed 50 mm during each consecutive tensioning process. If the horizontal displacement reaches this threshold, a 2 h pause should be observed before resuming the tensioning process. Furthermore, vigilant monitoring of the horizontal displacement at the mast's top should be maintained throughout the construction procedure. The cumulative displacement deviation at each stage of the mast's top displacement must not surpass 100 mm.

Based on the mentioned principles, the implementation of safety control for the cable net lifting process can be outlined as follows: Deploy monitoring devices to measure cable tension, displacement, and deformation during the cable net construction process. Transmit the collected data to the digital twin virtual model via sensors and wireless networks such as 4G or Wi-Fi. Monitor key points' displacement in the cable net structure and observe its structural morphology to assess the specific construction progress at the construction site. Compare the gathered construction data with simulation analysis results to evaluate the current safety status of the construction project. Utilize an artificial neural network (ANN) to forecast the forthcoming construction conditions of the cable net structure based on the ongoing monitoring data. Utilize the prediction outcomes to guide onsite construction, considering the extent of error. Perform real-time comparison and analysis of the collected data with the finite element simulation analysis data through a dedicated data processing center. Identify disparities between the onsite construction status and the simulation model. Display the outcomes of analysis and control in real time on the safety control twin platform, offering safety control services for cable net construction.

By implementing these steps, the safety control of the cable net construction process can be efficiently managed and monitored using the digital twin model, combining real-time data acquisition, analysis, prediction, and guidance. This comprehensive approach ensures effective safety control measures throughout the cable net construction process.

Table 3 shows the parameter values of the representative components of the stay cables and ring cables.

Table 3. Parameter values of representative components of stay cables and ring cables.

	Number	Length (mm)	Effective Cross-Sectional Area (mm^2)	Elastic Modulus (N/mm^2)	Density (kg/m^3)	Poisson's Ratio
Stay cables	K5-1b-L1	4118.6	4420	$(1.6 \pm 0.1) \times 10^5$	7850	0.3
Ring cables	XS1-3	53,170.7	11,000	$(1.6 \pm 0.1) \times 10^5$	7850	0.3

Obtain the cable force and configuration information during the construction process, transmit it to the twin model and compare it with the mechanical characteristics of the finite element simulation, analyze the error size of the construction process, judge whether it meets the specification requirements, and guide the site construction according to the analysis results. Through the application of this method, the real-time analysis and control of the construction process are realized. The cable network number is shown in Figure 12. Where CXZS is the load-bearing cable, WDS is the stabilizing cable, and H is the loop cable locking clip.

Figures 13–15 depict the evolution of load-bearing cable force, stable cable force, and ring cable clamp elevation during the lifting process. In each figure, (a) represents the outcome of finite element simulation analysis, while (b) presents the onsite construction process monitoring data. The discrepancy between the actual construction and simulation is determined through a corresponding analytical process, with the analysis results found to be within the acceptable margin of error. Should the error surpass the predefined threshold, a warning is issued at the construction site, triggering appropriate construction control measures. Conversely, if the error remains below the limit, construction proceeds, accompanied by continuous monitoring to ensure the completion of safety control measures.

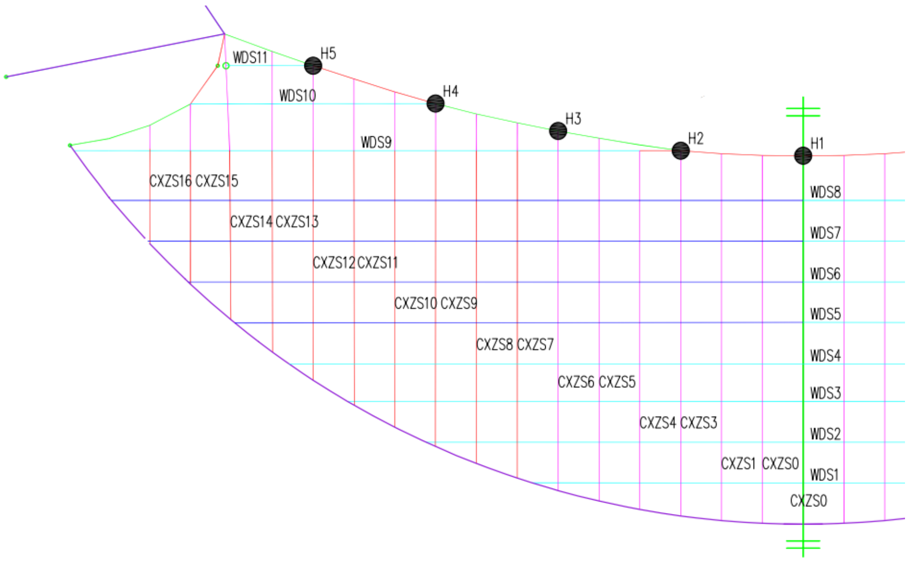
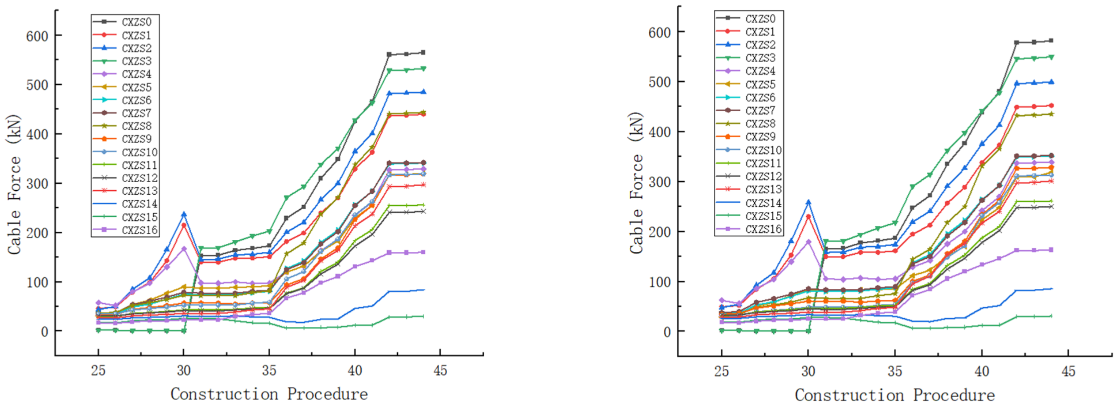
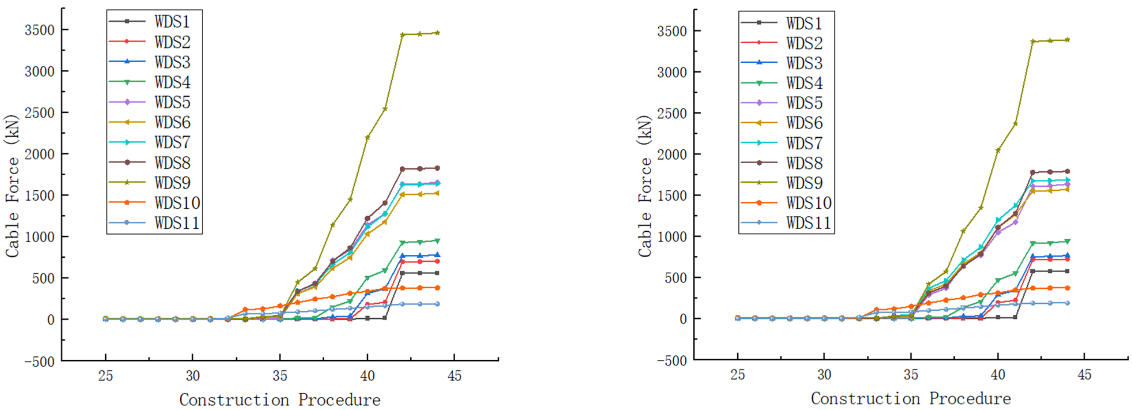


Figure 12. Cable network numbering diagram.



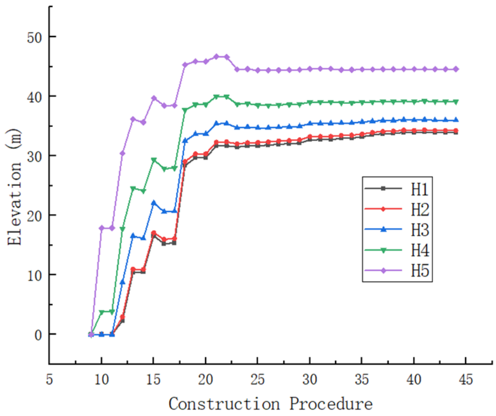
(**a**) (**b**)

Figure 13. Development process of load-bearing cable (ring cable side) cable force during the entire construction process: (**a**) finite element simulation analysis results; (**b**) monitoring data of onsite construction process.

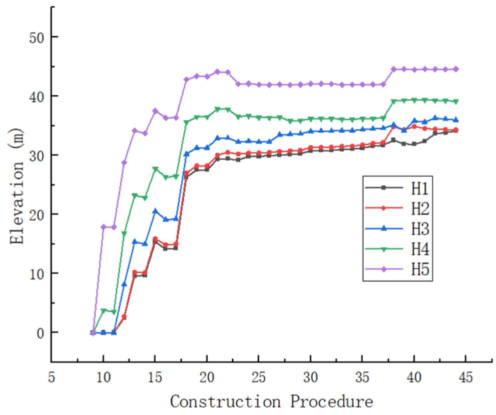


(**a**) (**b**)

Figure 14. Development history of stable cable force throughout the construction process: (**a**) finite element simulation analysis results; (**b**) monitoring data of onsite construction process.



(**a**)



(**b**)

Figure 15. Development history of the elevation of the ring cable clamp during the entire construction process: (**a**) finite element simulation analysis results; (**b**) monitoring data of onsite construction process.

Tables 4–6 compare the measured and predicted values of the weighing and stabilizing cable forces when the structure is about to reach its formed state and the measured and predicted values of the ring cable locking clamp elevation. From the table, it can be concluded that the prediction accuracy can be guaranteed at above 90%.

Table 4. Comparison of measured and predicted values of weighing cable force.

Number	Construction Steps	Predictive Value (kN)	Measured Value (kN)	Accuracy
CXZS1	gk41	363	386.3	94%
	gk42	437	483.1	90%
	gk43	438	471.5	93%
	gk44	440	469.4	94%
CXZS5	gk41	255	248.1	97%
	gk42	318	300.5	94%
	gk43	318	311.5	98%
	gk44	320	300.5	94%
CXZS9	gk41	255	262.7	97%
	gk42	317	342.8	92%
	gk43	317	336.5	94%
	gk44	319	328.6	97%
CXZS13	gk41	237	251.4	94%
	gk42	293	271.0	92%
	gk43	294	281.4	96%
	gk44	297	288.6	97%

Table 5. Comparison between measured and predicted values of stable cable forces.

Number	Construction Steps	Predictive Value (kN)	Measured Value (kN)	Accuracy
WDS3	gk40	316	292.9	93%
	gk41	371	343.9	93%
	gk42	765	734.8	96%
	gk43	767	751.6	98%
WDS5	gk40	1142	1049.5	92%
	gk41	1275	1171.7	92%
	gk42	1632	1534.8	94%
	gk43	1635	1584.6	97%

Table 5. *Cont.*

Number	Construction Steps	Predictive Value (kN)	Measured Value (kN)	Accuracy
WDS8	gk40	1221	1109.9	91%
	gk41	1407	1315.8	94%
	gk42	1815	1694.3	93%
	gk43	1820	1765.4	97%
WDS10	gk40	338	313.3	93%
	gk41	375	347.6	93%
	gk42	379	357.2	94%
	gk43	381	373.4	98%

Table 6. Comparison of measured and predicted elevations of ring rope locking clamps.

Number	Construction Steps	Predictive Value (m)	Measured Value (m)	Accuracy
H2	31	33.25	30.1	91%
	32	33.26	30.5	92%
	33	33.43	31.5	94%
	34	33.47	32.4	97%
H3	31	35.46	33.4	94%
	32	35.47	34.1	96%
	33	35.53	34.2	96%
	34	35.54	34.6	97%
H5	31	44.64	40.3	90%
	32	44.62	40.9	92%
	33	44.46	41.9	94%
	34	44.46	42.3	95%

5. Conclusions

This article introduces a novel safety control approach for the construction process of traditional cable net structures, leveraging the concept of digital twinning. The method is designed to address safety concerns inherent in conventional cable net construction procedures. By creating a digital twin model for safety control, real-time monitoring and regulation of cable net construction activities onsite are accomplished. This approach seamlessly integrates mechanical and geometric information of the cable net structure with finite element simulation outcomes, allowing for continuous comparative analysis of construction changes observed at the site. As a result, the method significantly bolsters safety control capabilities throughout the construction phase. The article also encapsulates spatiotemporal data modeling and representation strategies in cable net structure construction and explores the practical implementation of digital twinning to enhance safety control. Through practical engineering implementations, the method's viability was showcased, leading to noteworthy improvements in safety control standards and a reduction in potential construction hazards. This research not only presents fresh insights but also introduces innovative technical avenues for augmenting the safety oversight of cable net structures, contributing to a more meticulous and effective construction management approach.

(1) This article introduced an innovative approach to address the safety control challenges of cable net structures during construction. By recognizing the limitations in the existing safety control practices, this article proposed a novel method grounded in the concept of digital twinning. This approach, termed "time-space-aware safety control," aimed to bridge the gap and provide a comprehensive solution. Through the establishment of a digital twin model for safety control, the method offered a promising avenue for improving the overall safety oversight of cable net structures. Through this method, the control accuracy of the measured and predicted comparison of the cable net structure can reach 90%, and the control efficiency is also greatly

improved. In addition to the neural network algorithm, other algorithms are also applied, such as support vector machine (SVM) and support vector regression (SVR), but the accuracy is not satisfactory, only up to 84%.

(2) This article provided a comprehensive overview of the strategies and techniques for spatiotemporal data modeling and representation in the context of constructing cable net structures. The focus was placed on achieving real-time monitoring throughout the construction process. The article delved into key components such as data collection, transmission, model creation, analysis of results, and the establishment of a decision-making framework. By thoroughly exploring the practical application of digital twinning, this article offers insights into leveraging this approach for enhanced safety control in the construction of cable net structures.

(3) By implementing this method in real-world engineering scenarios, the viability of the approach was demonstrated, validating its potential to achieve heightened precision in construction safety management. Through the utilization of real-time monitoring and control, construction teams gained deeper insights into the dynamic alterations in cable net behavior throughout the construction stages. This substantial enhancement in safety control effectively mitigated construction-related risks, fostering a safer construction environment.

(4) To ensure the analysis efficiency of the model, the accuracy and quality of the model are reduced to a certain extent. The efficiency of data transmission also needs to be improved. Future research can focus on improving the quality and integration of model data, such as optimizing model algorithms, using high-precision sensors, and data fusion techniques to obtain more accurate and comprehensive construction data. In addition, this method can be extended to different types of structures, such as bridge construction scenarios.

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