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Research Article

The Influence of the Inclination of Lattice Columns on the Safety of Combined Tower Crane

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The combined tower crane foundation is widely used in construction sites due to its advanced utilization rate. However, the immature construction method, unavoidable construction deviation during the installation process, and influence of the surrounding construction generally cause the lattice columns to tilt. As the main force transmission components of the tower crane foundation, once its stress and deformation exceed the limit, the entire tower crane will collapse, which requires engineers to accurately control its safety. Therefore, the objective of the work reported here was to study the safety of the lattice columns during operation. A geometrically nonlinear finite element model was utilized to simulate the strain and deformation capacity of tower cranes under various working conditions, including vertical and inclined working conditions, operation and shutdown conditions, and conditions with the tower boom in different orientations. In addition, this study combines the simulation with the on-site measurement. The results of on-site measurement were also recorded to verify the correctness of the proposed calculation model. It was concluded that the inclination of lattice columns has a significant effect on the deformation and stress of the lattice columns of the tower crane foundation, and the measured data and the calculated data trend are consistent. Engineers can accurately judge the safety of the lattice columns of the tower crane foundation through geometric nonlinear finite element model analysis and on-site monitoring to avoid the failure of the lattice columns and the occurrence of safety accidents.

1. Introduction

The combined tower crane foundation is a foundation with several steel lattice columns or steel pipe piles connected to the lower end and a concrete cap or section steel platform connected to the upper end [1]. Figure 1 shows the combined tower crane foundation, which is a kind of high pile cap foundation. The lower segment of the lattice columns is embedded during the construction of the cast-in-place pile, and the upper segments of the lattice columns are poured with reinforced concrete as the upper cap. The anchor bolts or supports are embedded to connect the standard sections of the tower crane. The upper load of the tower crane is transferred to the lattice columns through the cap and then transferred to the pile foundation through the lattice columns. The traditional tower crane foundation is placed around the foundation pit, resulting in limited tower crane transportation capacity and low utilization rate [2]. Consequently, the combined tower crane foundation can be constructed simultaneously with the pile foundation. It can be installed and put into use before the excavation of the foundation pit. The advantages of the tower crane in horizontal and vertical transportation can be effectively used to improve the construction efficiency and greatly shorten the construction period. Therefore, the combined tower crane foundation is used more and more extensively [3].

According to the statistics, hundreds of tower crane accidents occur in China every year. The main causes of the

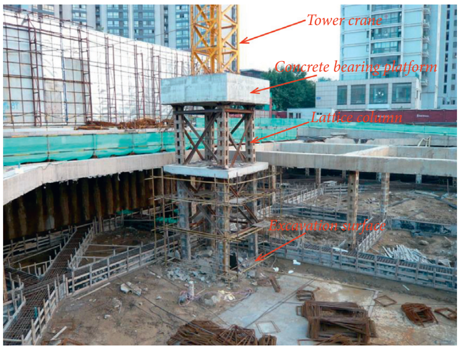

Figure 1: The combined tower crane foundation.

Figure 2: Collapsed tower crane.

accidents are foundation instability, foundation inclination, loose bolts, and overweight cranes [4]. Figure 2 shows a picture of the collapsed tower crane.

Most previous studies on the safety of tower cranes were mainly conducted through on-site monitoring and finite element simulation analysis. Several research results have been obtained. Chen et al. [5] monitored the real-time running state and solved the overloaded security issues of tower cranes through monitoring and analyzing critical parameters of a tower crane. In their studies, the structure of the tower crane safety monitoring and protection system based on the ARM and multi-sensor was established, and the software system was designed with the modular structure and multithread technology with a friendly interface, which shows the real-time key information of tower crane safety monitoring and protection system. To accurately describe the dynamic performance of the tower crane and ensure its safety and high efficiency, Wang et al. [6] innovatively used the space vector mechanics theory in the dynamic analysis of the tower crane operation state to induce and provide a method for calculating hoisting load under combined operation condition. They used ANSYS to analyze the complicated situation of hoisting, rotation, and luffing and proposed a set of effective dynamic design theories of the tower crane. Chen et al. [7] took the QTZ630 tower crane as the research object and adopted the parameter language APDL which was used to model ANSYS to set the basic parameters of the material and the grid and finally performed a static analysis. Combined with the actual situation, the normal operation of the tower crane under three different deformation and internal force conditions was analyzed. The results showed that the maximum displacement and stress values of the three operating conditions meet the design requirements and specifications, and there was still material balance. Lu and Wen [8] studied the influence of a single limb's instability on the entire structure. The moment balance method was used to deduce the precise internal force expression of the structure under the combined load. At the same time, the decoupling support stiffness of the connecting device in all directions was obtained by the unit load method. Based on the refined calculation model, under the condition that the unstable rod bore the fixed Euler critical force, the internal force was further analyzed, and the structural strength and stability ability were judged. The calculation results showed that the entire structure had greater bearing potential after partial buckling. Gan et al. [9] established a finite element model for the upper and lower slewing support structure of a large flat-top tower crane, and they analyzed the force of the upper and lower slewing support under different operation conditions through the finite element method and judged whether its overall structure was reasonable and met the strength requirements; finally, they optimized the structure on this basis. Because of the uneven stress distribution of the upper rotary support, parameter adjustments and local structural improvements were made to make the stress distribution more uniform; the weak parts of the lower rotary support were strengthened locally to reduce the maximum stress. Zhang and Liu [10] designed a tower crane wireless monitoring and management system based on Modbus/TCP protocol for the distributed, efficient, and safe operation of tower cranes. Based on Cortex A8 and Win CE6, the front end of system monitoring was designed to monitor the status information of tower crane operation in real time. Yu et al. [11] established a BP neural network model to monitor the online operating status of the tower crane and conducted simulation experiments on the stability of the model. The results showed that the BP neural network model can accurately monitor the operating status of the tower crane and effectively predict failures. In addition, it can improve safety and reliability. Li et al. [12] used MATLAB and ANSYS to perform finite element simulation on the tower crane support system and verified the practicability of the tower crane support system. Hamit and Azeloglu [13] used MATLAB to analyze the dynamic response characteristics of the tower crane support system and studied the seismic performance of the support system. Yao et al. [14] used ANSYS to perform eigenvalue buckling analysis and geometric nonlinear buckling analysis of a 500-ton all-terrain combined boom system. In their analysis, the jib, dead weight, offset load, wind load, and lifting rope force during tower lifting were considered. Then, the influence of combination relationship of the length of the eccentric structure strut, the opening angle, the luffing angle, the length of the super-lifting device strut, the opening angle, and the changing angle on the overall stability of the combined arm system was obtained.

As to the safety research of the tower crane, Chen et al. [15] used the autoregressive method to simulate the time history of the wind load and applied it to the finite element model to analyze the impact of wind load on the tower crane's vibration and the impact of fluctuating wind loads on the tower crane's safety. Trong and Khiem [16] used the dynamic stiffness method to treat the cracks of the tower crane, where the cracks were equivalent to springs, and established a model for typical modal analysis to evaluate the safety of the tower crane. Kanan and Azeloglu [17] scaled the tower crane model by similarity theory to facilitate its application in experimental research. Based on the finite element method, a model that can calculate the natural frequency and quality factor and draw the structural mode shape composed of space frame elements was developed to study the safety of the tower crane. Stölzner et al. [18] analyzed the dynamic behavior of a tower crane during the important work process of slewing. The results of the approach according to the standards were compared with the results of the nonlinear dynamic finite element calculation. In addition, a newly developed vibration model based on a two-mass model was proposed. The model helped to estimate the dynamic loads more accurately than the methods currently used, and the computation time required to perform the stress calculation was only slightly increased.

According to the current research status at home and abroad, the safety research of tower cranes mainly focuses on external loads such as wind loads and the structure itself. The dynamic characteristics of tower cranes are determined through modal analysis, but there is a lack of research on the safety of tower cranes caused by deviations caused by construction. Research scholars mainly use finite element analysis and on-site monitoring methods to study the safety of tower cranes, and the research methods are feasible. The deviation caused by construction cannot be avoided in the project, but it is one of the main causes of engineering accidents. The foundation of the combined tower crane adopts the construction method of preburied lattice columns, which has certain convenience, but it is difficult to control the verticality of lattice columns in underground construction. After the lattice columns were leaned during construction, engineers will face how to judge the safety of the tower crane. For this, this paper uses geometric nonlinear finite element models and on-site monitoring methods to study the effect of the lean of the lattice columns on the safety of the tower crane foundation and provides a reference for the engineering staff to judge the safety of the tower crane.

2. Analysis of the Causes of Inclination of Lattice Columns

For the combined tower crane foundation, the lattice columns are the main force transmission members. Once the stress or deformation exceeds the limit, the tower crane will collapse as a whole, causing casualties and economic damage. Due to the influence of construction technology and external factors, lattice columns often lean and exceed the deviation of the specification requirements. The reasons for the tilt of the lattice column are analyzed below.

2.1. Installation Reasons. The lattice columns need to be embedded in the ground during the foundation installation of the combined tower crane. The actual verticality cannot be checked during the embedded process, and the construction quality cannot be judged. As a result, the lattice columns are found to be leaned during the excavation process.

2.2. Deformation of the Surrounding Foundation Pit. The combined tower crane foundation has been put into use normally before the earthwork excavation. Due to the construction organization, the earthwork excavation is carried out in different regions. When the surrounding earthwork at the tower crane foundation is excavated and supporting structures are not constructed timely, the earthwork slope will be deformed. Therefore, the lattice columns will lean under the earth pressure.

3. Finite Element Analysis

3.1. Geometric Nonlinear Finite Element Analysis Method. In the analysis of linear elastic mechanics, it is assumed that the relationship between displacement and strain is linear and the strain is small, and thus the linear geometric equations can be obtained. When considering the nonlinear relationship between displacement and strain or using large strain theory (finite deformation theory), it is a geometric nonlinear problem. Nonlinear problems include large displacement with small strain and large displacement with large strain, which all lead to the geometric equation of motion becoming nonlinear, but the constitutive relationship of the material still conforms to Hooke's law [19].

Geometric nonlinearity is caused by large displacements of structural deformation. In this situation, the structures will produce large deformation and displacement. The deformation process can no longer be directly described by the position and shape when no force is applied. Besides, the geometric position of the equilibrium state is also unknown, and new definitions of stress and strain must be given [20]. Due to the lattice column foundation of the tower crane is a cantilever structure, there is an initial deviation in the installation position of the lattice column, the upper loads are constantly changing, and the lattice columns have a large displacement under the forces, so the geometric nonlinear influence of the lattice columns needs to be considered.

3.2. The Process of Building the Model. This paper took a tower crane foundation with lean lattice columns as an example and analyzed the influence of the lean lattice columns on the safety of the tower crane through the geometric nonlinear finite element model. The model of the lattice columns of the combined tower crane was established according to the measured coordinates on-site, and the initial inclination of the lattice columns was considered. The inclination of the unexcavated part of the lattice columns was linearly extended according to the excavated coordinates. Midas/GEN was used to establish the geometric nonlinear finite element analysis model. The main steps of the geometric nonlinear finite element analysis of lattice columns are as follows.

3.2.1. Establishing a Geometric Model. The foundation of the combined tower crane was equipped with 4 steel lattice columns. The cross section size of the combined lattice columns is 2950 mm × 2950 mm. The single lattice column used a combined section of 450 mm × 450 mm. The main limb adopted 4 L180 × 18 angle sheets of steel. The patch board adopted a cross section size of 424 mm × 300 mm × 20 mm with a spacing of 610 mm. Their material strength was Q235B. A horizontal connecting rod and horizontal cross brace were arranged every 2.4 m for the combined lattice columns, and the cross braces were located inside the combined lattice columns. The cross-sectional size of the upper cap was 4200 mm × 4200 mm × 1600 mm, and the cross-sectional size of the lower cap was 4000 mm × 4200 mm × 200 mm. Due to the deviation of the on-site lattice columns during installation, the inclination of the steel lattice column of the tower crane was re-measured when the foundation pit was excavated to the elevation of the floor cushion. The results showed that the steel lattice columns of the tower crane deviated and inclined in the same direction. The plane position and lean deviation values of the steel lattice columns of the tower crane are shown in Figure 3.

3.2.2. Determining the Constraints. The lattice columns were inserted into the cast-in-place piles to a depth of 3 m, so the bottom of the lattice columns was restrained by fixed support.

3.2.3. Applying Loads and Load Combination. Since the lattice columns were in the foundation pit, the effect of wind load was not considered in the analysis and calculation, that is, the steel lattice column mainly bore the load transmitted by the tower crane. The installation height of the tower crane was 49 m, and the boom length was 54 m. According to the manual of STT293 tower, the tower crane adopts 16 standard sections, and the foundation load is shown in Table 1. In the table, M_V represents the bending moment transferred from the tower crane to the foundation, F_h represents the horizontal force transferred from the tower crane to the foundation, and F_V represents the vertical force transferred from the tower crane to the foundation. Operation conditions refer to the state of the tower crane in hoisting operation, idling operation, or intermittent shutdown. Out-of-operation conditions refer to the tower crane in the conditions of not operating and not lifting heavy objects and in a static state.

The load combinations were carried out according to the operation conditions and out-of-operation conditions of the tower crane, and the load combinations are shown in Table 2. The ratio of the weight of the components used on-site to the weight of the calculated model was about 1.05. Therefore, to ensure the accuracy of the model, the self-weight coefficient was multiplied by 1.05.

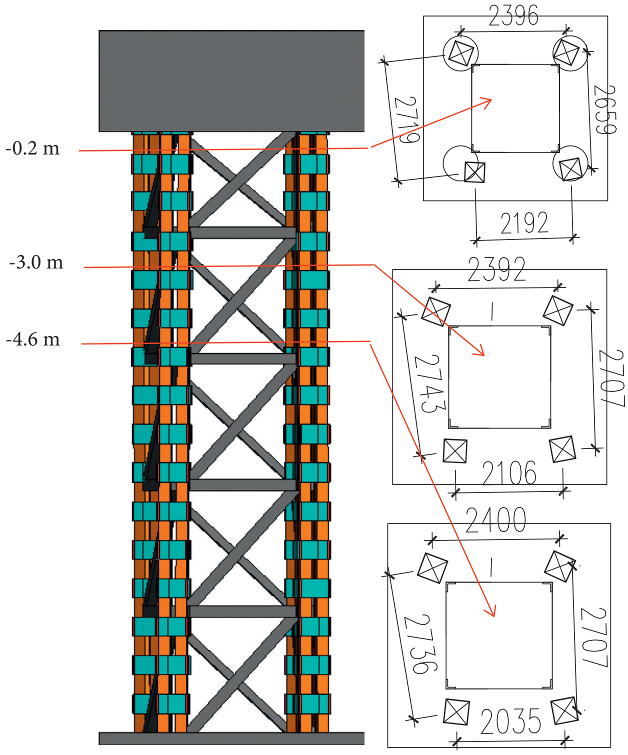

Figure 3: Plane position and lean deviations of steel lattice columns of the tower crane.

Table 1: Basic loads.

Loads	Operation conditions	Out-of-operation conditions
M_V	3838 kN·m	3280 kN·m
F_h	37 kN	131 kN
F_V	1384 kN	1045 kN

3.2.4. Setting Up Geometric Nonlinear Analysis. The lattice columns of the tower crane foundation themselves were deformed, and the deformation would continue to increase as the load increased. Therefore, this model needed to consider geometric nonlinearity. The calculation method used was the Newton–Raphson method, the number of loading steps was 10, and the number of iterations in the substep was 30. The convergence condition adopted displacement control, and the control value was 0.01 mm. Figure 4 shows the finite element model.

3.2.5. Content of Analysis

(1) Comparing and analyzing the deformation and stress of the tower crane in the vertical state and the inclined state.

(2) Comparing and analyzing the deformation and stress of the tower arm at different angles (0 degrees, 45 degrees, 90 degrees, 135 degrees, 180 degrees, 225 degrees, 270 degrees, and 315 degrees) in the inclined state. Figure 5 shows a schematic diagram of the angles of the tower crane.

3.3. The Deformation and Stress of the Tower Crane in the Vertical State and the Inclined State. When the tower arm was at 0 degrees, the maximum deformation and stress of the lattice columns in the vertical state and the inclined state

Table 2: Load combinations.

Combination numbers	Combination formulas	Combination types
COMB1 (operation condition)	$1.0 \times 1.05 \times$ self-weight $+ 1.0 \times M_V$, F_h, F_V in operation condition	Standard combination
COMB2 (out-of-operation condition)	$1.0 \times 1.05 \times$ self-weight $+ 1.0 \times M_V$, F_h, F_V in out-of-operation condition	
COMB3 (operation condition)	$1.35 \times 1.05 \times$ self-weight $+ 1.35 \times M_V$, F_h, F_V in operation condition	Basic combination
COMB4 (out-of-operation condition)	$1.35 \times 1.05 \times$ self-weight $+ 1.35 \times M_V$, F_h, F_V in out-of-operation condition	

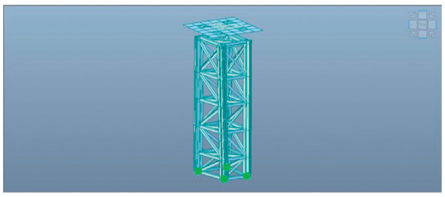

Figure 4: The finite element model.

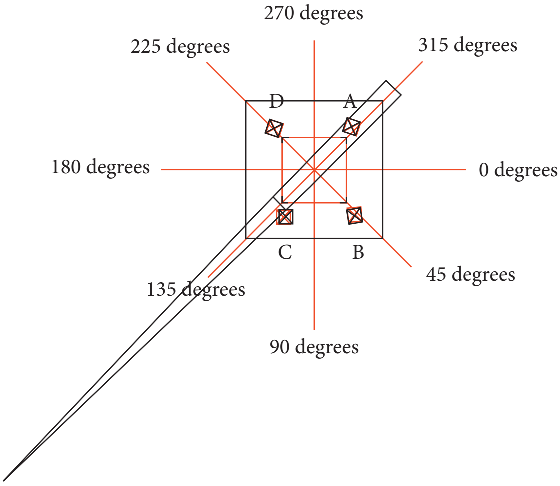

Figure 5: Schematic diagram of the angles of the tower crane.

under operation conditions and out-of-operation conditions were analyzed. Figure 6 shows the deformation and stress diagram of the lattice columns in the vertical state, and Figure 7 shows the deformation and stress diagram of the lattice column in the inclined state.

The finite element analysis results of the lattice columns in Figures 6 and 7 were compared and analyzed. To facilitate the image comparison, a three-dimensional histogram was used to show the deformation comparison results, as shown in Figure 8, and the stress comparison results are shown in Figure 9. It can be seen from the comparison results that the deformation and stress of the lattice column under out-of-operation conditions are greater than those under operation conditions, no matter in the vertical state or the inclined state. Under the two operation conditions, the lean caused by the construction led to significant increases in the deformation and stress of the lattice columns. The maximum deformation of the lattice columns increased by 38%, and the stress increased by 8%.

3.4. Maximum Deformation and Stress of Lattice Column under Different Orientations of Tower Arm. When the tower arm is at 0 degrees, 45 degrees, 90 degrees, 135 degrees, 180 degrees, 225 degrees, 270 degrees, and 315 degrees, the geometric nonlinear analyses of the lattice columns of the tower crane foundation were carried out. From the analysis results, it can be seen that the deformation and stress of the lattice columns of the tower crane in the out-of-operation condition were greater than those in the operation condition, that is, the tower crane was more dangerous in the out-of-operation condition than in the operation condition.

The maximum deformation and maximum stress of the lattice columns of the tower crane foundation were statistically analyzed when the tower arm was in different orientations. The results of the deformation analysis are shown in Figure 10, and the results of the stress analysis are shown in Figure 11. The red curve represents the out-of-operation condition, and the blue curve represents the operation condition. When the tower arm was at 0 degrees, the lattice columns deformed the most, and the deformation value was 18.25 mm in out-of-operation condition and 16.59 mmin operation condition. When the tower arm was at 270 degrees, the deformation of the lattice columns was the smallest, and the deformation value was 11.66 mm in out-of-operation condition and 10.26 mm in operation condition. When the tower arm was at 135 degrees, the stress of the lattice columns was the largest, and the stress value was 142.65 MPa in out-of-operation conditions and 131.47 MPa in operation conditions. When the tower arm was at 90 degrees, the stress of the lattice columns was the smallest, and the stress value was 98.69 MPa in out-of-operation conditions and 93.07 MPa in operation conditions. According to the results of deformation and stress analysis, the deformation and stress of the lattice columns were quite different when they were inclined and caused the tower arm to be in different orientations. Due to the inclination of the lattice column, the deformation and maximum stress of the lattice column were inconsistent, which indicated that the inclination of the lattice columns had a great influence on its forces.

4. On-Site Measurement

Two stress monitoring points were arranged on the lattice columns with larger deviation and the lattice columns with the largest supporting axial force, and one stress monitoring point was arranged on each of the remaining 2 lattice columns, and the measuring points were arranged 0.5 m upward from the lower bearing platform. The stress was measured by a vibrating wire strain gauge and calculated according to the elastic modulus of the material. The readings of the vibrating wire strain gauge were read by a full-function acquisition module, which realized wireless real-time acquisition. The stress measurement points are shown in Figure 12.

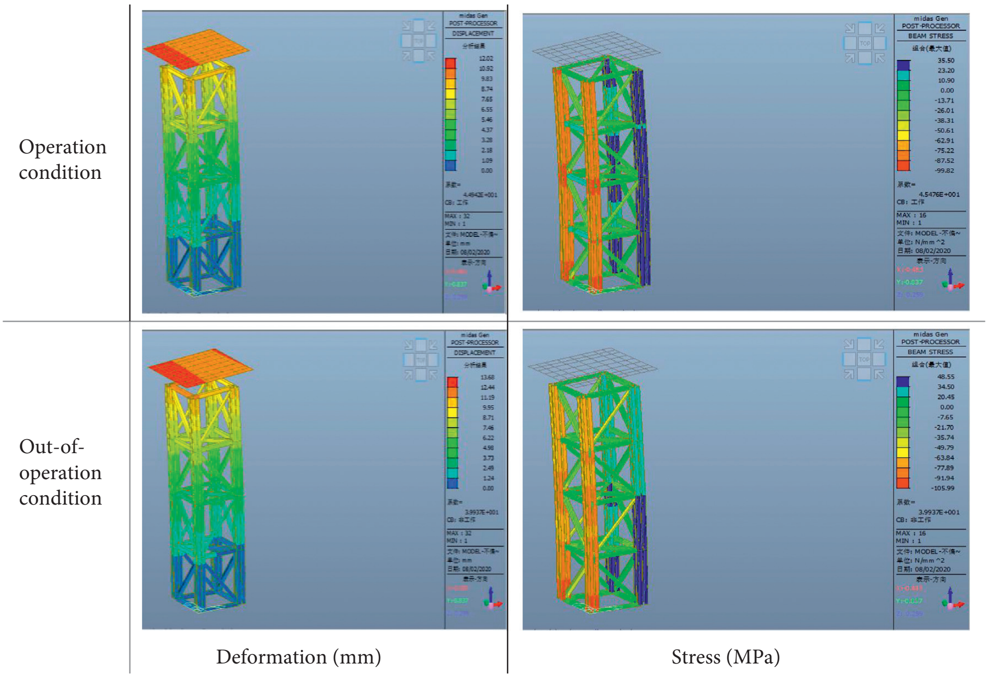

Figure 6: Deformation and stress of lattice columns in a vertical state.

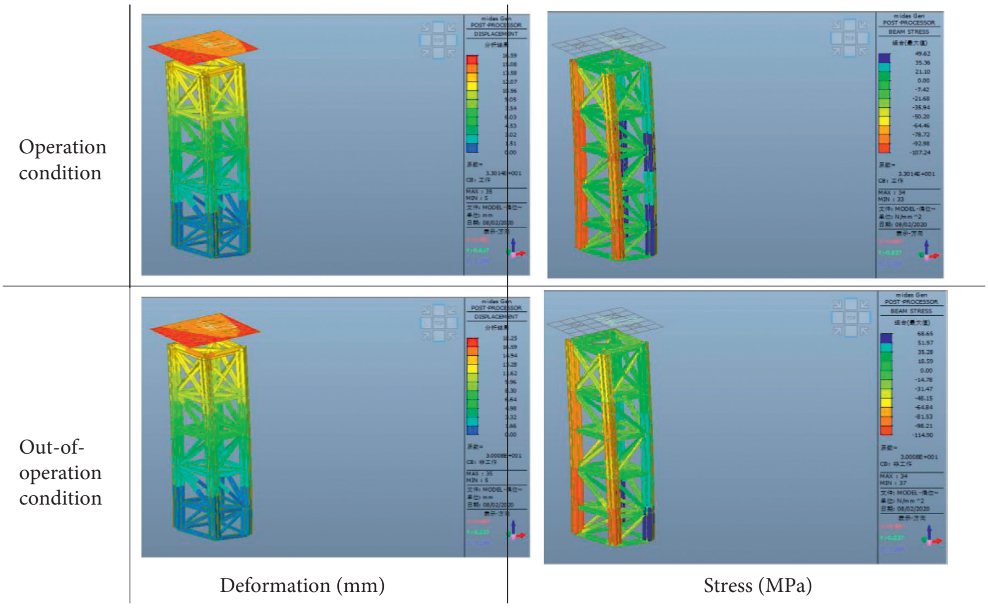

Figure 7: Deformation and stress of lattice columns in an inclined state.

According to the results of the finite element analysis, the lattice columns were dangerous when the tower crane was in out-of-operation condition. Therefore, the different positions of the tower crane in out-of-operation conditions were monitored, and the monitoring results were compared with the calculated values. The results are shown in Figures 13–16.

According to the measured stress values of the lattice columns under different orientations of the tower arm on-site, the stress of the lattice columns changed with the rotation of the tower crane, and the law of change was consistent with the finite element calculation results, indicating that the geometric nonlinear calculation model is reliable. The measured results show that the maximum stress of the A lattice column was 112.44 MPa, the maximum stress of the B lattice column was 88.48 MPa, the maximum stress of the C lattice column was 108.12 MPa, and the maximum stress of the D lattice column was 93.05 MPa. Compared with the finite element analysis results, the measured stress of the lattice column was lower, indicating that the actual structure had a higher safety factor than the finite element calculation model.

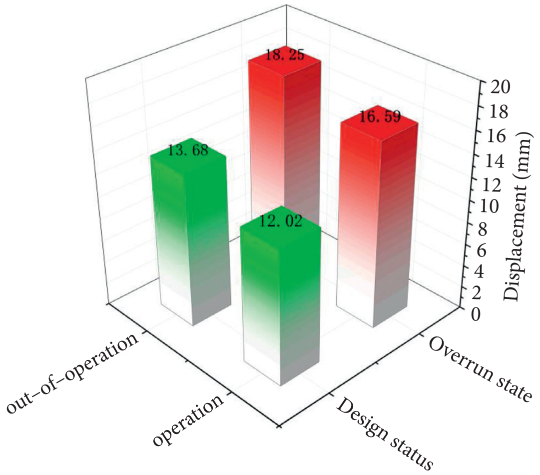

Figure 8: Deformation of the lattice columns in the vertical state and inclined state.

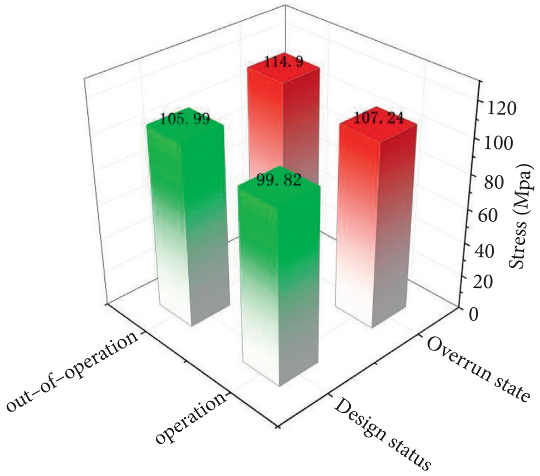

Figure 9: Stress of the lattice columns in the vertical state and inclined state.

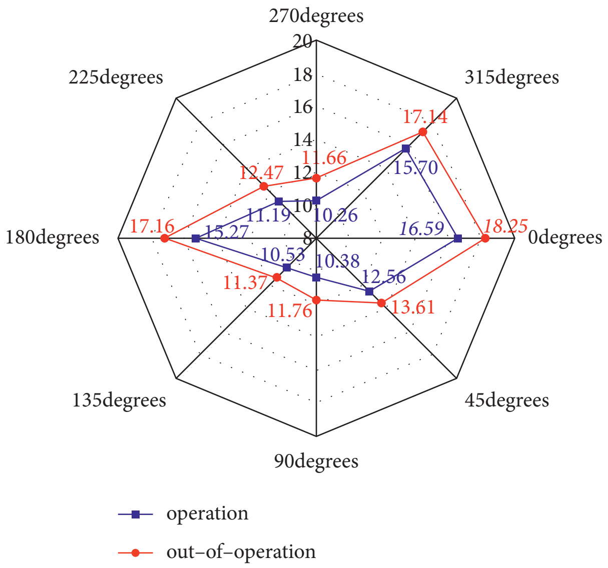

Figure 10: Maximum deformation of lattice columns in different orientations of the tower arm in operation condition and out-of-operation condition (mm).

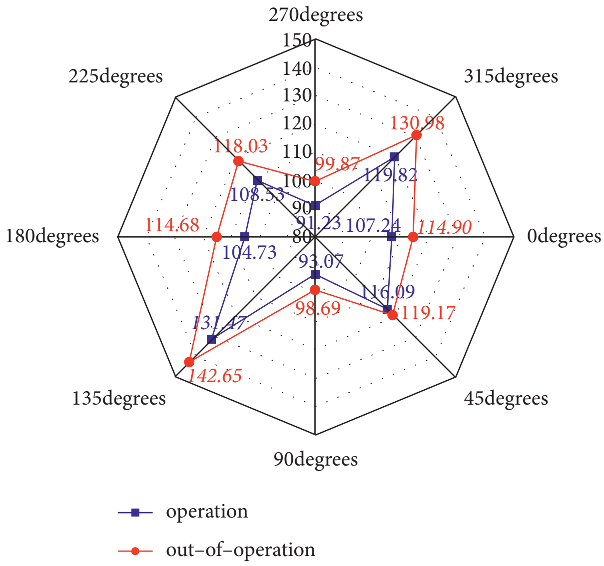

Figure 11: Maximum stress of lattice columns under different orientations of the tower arm in operation condition and out-of-operation condition (mm).

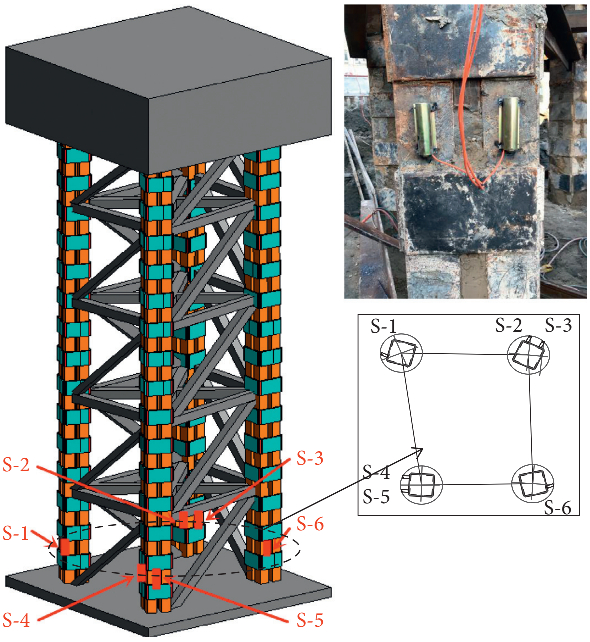

Figure 12: Stress measurement points.

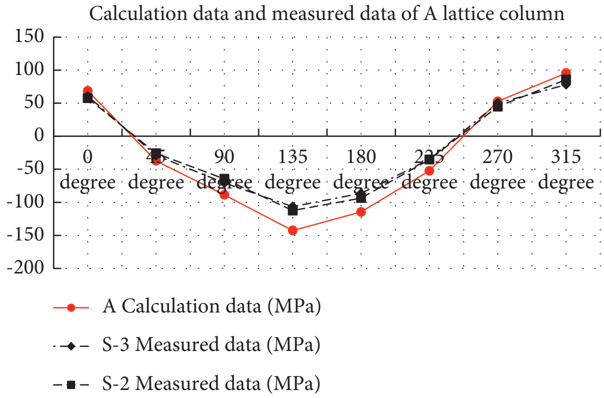

Figure 13: Comparison chart of calculated stress and measured stress of A lattice column.

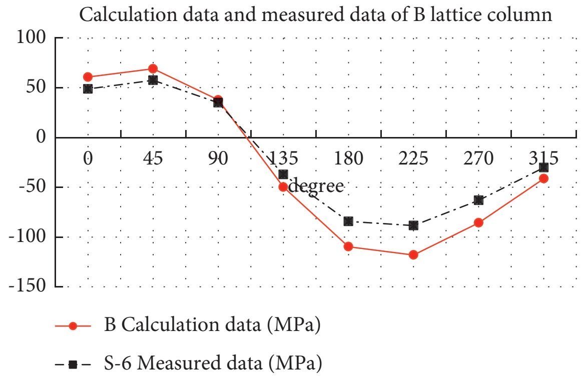

Figure 14: Comparison chart of calculated stress and measured stress of B lattice column.

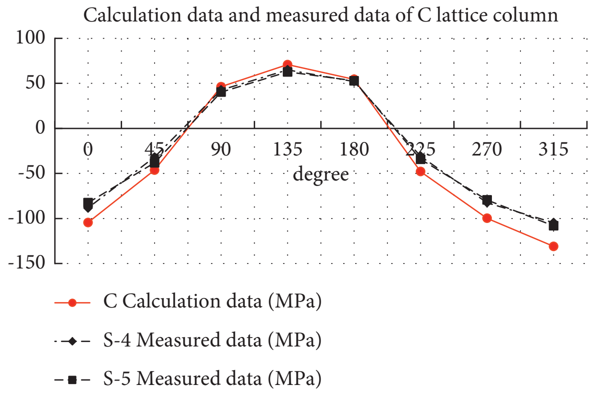

Figure 15: Comparison chart of calculated stress and measured stress of C lattice column.

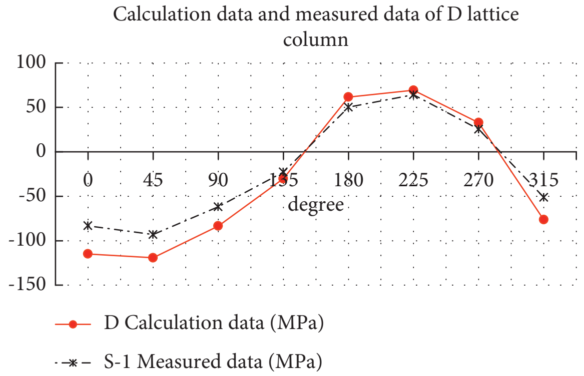

Figure 16: Comparison chart of calculated stress and measured stress of D lattice column.

5. Conclusion

The combined tower crane foundation is widely used due to its high utilization rate, and the lattice columns lean due to installation reasons or the deformation of the surrounding foundation pit. Hundreds of tower crane collapse accidents occur every year, which is bound to arouse the attention of engineers. Technicians need to judge whether the lattice column foundation of tower crane with initial defects can be used safely, and their decision directly affects the safety of personnel and property. Therefore, this paper combines the safety of a tower crane foundation with inclined lattice columns, and the research results are as follows:

(1) The deformation and stress of the lattice columns with inclination have increased compared with the lattice column without inclination. The deformation of the lattice columns has increased by 38%, and the stress has increased by 8%.

(2) The deformation and stress of lattice columns under out-of-operation conditions are greater than those under operation conditions.

(3) When the tower arm is at 0 degrees, the lattice column deforms the most; when the tower arm is at 270 degrees, the lattice column deforms the least. When the tower arm is at 135 degrees, the lattice column stress is the largest; when the tower arm is at 90 degrees, the lattice column stress is the smallest.

(4) The geometric nonlinear finite element calculation results of the measured stress of the lattice column have the same trend, which verifies the reliability of the geometric nonlinear calculation model.

(5) Through finite element model analysis and on-site measurement, the safety of the tower crane can be judged. For such problems, this method can be used to ensure the safety of the tower crane. For the inclined lattice columns of the tower crane foundation, the finite element simulation should be performed first to evaluate its safety, and then according to the finite element analysis results, whether the lattice columns of the tower crane foundation need to be reinforced can be determined.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Yongquan Wang was responsible for methodology, formal analysis, and original draft preparation. Tianfu Li was responsible for validation, visualization, and investigation. Kaifa Dong was responsible for supervision and funding acquisition. Zhengxing Guo was responsible for investigation, conceptualization, resources, and project administration. Jing Fu was responsible for investigation.

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