Journal of Engineering Science and Technology Review 14 (6) (2021) 72 - 82

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Research Article

A Finite Element Analysis-based Study on the Reliability of Heightened Quayside Container Cranes

Dazhi Huang[1,*], Xiaoqiang Guo[2], Haichao Wang[3], Hao Wang[4] and Yang Peng [5]

[1]*School of Ocean Engineering, Jiangsu Ocean University, Lianyungang 222005, China*
[2]*School of Mechanical Engineering, Jiangsu Ocean University, Lianyungang 222005, China*
[3]*Xindongfang International Container Company of Lianyungang，Lianyungang 222042, China*
[4]*Testarc Technologies Co.,Ltd. Beijing 100029, China*
[5]*Department of Electrical Engineering, Wayne State University, Detroit, MI 48202, United States*

Received 12 August 2021; Accepted 23 December 2021

Abstract

With the ever-increasing size of container ships, the lifting height of most in-service quayside container cranes (hereinafter referred to as quay cranes) can no longer adapt to the new demands. In order to enable quay cranes to lift containers from 18,000 twenty-foot equivalent unit (TEU) ships, the world's ports are now developing crane heightening technology. However, the structure of heightened quay cranes undergoes changes that affect their reliability. In this study, finite element analysis (FEA) was employed to analyze the structural reliability of heightened quay cranes. In the case of the 61t-55m Quay Crane Heightening Project at Lianyungang Port, eight operating conditions were identified using the FEA software ANSYS. The static and dynamic characteristics of the metal structure for the heightened quay crane were simulated and experimentally analyzed. The stresses and deformations at various observation points were compared when the trolley was in different critical positions. The stress and displacement nephograms of the quay crane metal structure under different operating conditions were derived, and the structural reliability of the hydraulically heightened quay cranes was verified. Results showed that the maximum stress of the sea side column is 224.76MPa, and the maximum stress of the road side column is 195.19MPa, both of which are less than the allowable stress, when the modal frequency is from 0.261Hz to 3.555Hz, the structural vibration is stable, the overall stiffness and stress of the quay crane metal structure meet the safety requirements. This study provides an important reference for the heightening modification and metal structure reliability assessment of quay cranes.

Keywords: Quay crane heightening, Finite element analysis, ANSYS, Static analysis, Modal analysis

1. Introduction

Quayside container cranes (hereinafter referred to as quay cranes) are the primary equipment for loading and unloading containers between container ships and quaysides because of their large load capacity and high operating efficiency. With the emergence of "Hyundai Merchant Marine(HMM) Algeciras", a 24,000 twenty-foot equivalent unit (TEU) super-large container ship, the container stacking height on ships has been increasing continuously [1]. According to the current manufacturer status, the current crane loading/unloading height in the Quay Crane Heightening Project at Lianyungang Port is 40 m above the rail, which cannot meet the ship type demands. Container loading/unloading bridges with heights higher than seven floors on the deck have been unable to complete unloading. Existing quay cranes cannot adapt to new demands regarding lifting height and outreach [2]. Accordingly, the world's ports are now developing quay crane heightening technology to address the current problems [3].

After heightening modification, the outreach and lifting height of quay cranes will increase evidently, and the crane structure will undergo a series of changes that will affect the structural reliability of the quay cranes. How to determine the reliability and operational safety of quay crane structures after heightening modification appears to be particularly important. Thus, identifying the structurally critical points and performing strength, stiffness, and modal analyses with a reliable finite element analysis (FEA) model are of profound significance to the structural stability and safety of quay cranes [4,5].

Given the above findings, extensive studies have been carried out concerning the heightening modification and reliability evaluation of quay cranes. However, all of these studies remain one-sided, which cannot resolve the deviation of FEA results from the actual performance of heightened quay cranes. Hence, it is imperative to develop a method to accurately determine the safety and reliability of quay crane structures after heightening modification.

To this end, this study attempted to increase the overall height of the 61t-55m quay cranes at Lianyungang Port by 6 m via the fully automatic hydraulic jacking technique. The FEA model of the quay crane metal structure was created on the ANSYS platform, and static calculation and modal analysis were performed on the metal structure under typical operating conditions. The objectives of this study are to determine more accurately the safety performance and stability of heightened quay cranes, thereby providing an important reference for the heightening modification of quay cranes and the reliability assessment of crane metal structures.

*E-mail address: strong_guo@163.com
ISSN: 1791-2377
doi:10.25103/jestr.146.08

2. State of the art

To date, extensive studies have been carried out concerning the heightening modification and FEA of quay cranes. Sun Y.T. et al. [6] analyzed the failure modes and influences of quay crane heightening construction based on fuzzy set theory, which improved the accuracy of failure mode and effects analysis (FMEA) but failed to analyze the overall metal structural stress in detail. Adopting the steel-strand lifting method, Lin C. [7] controlled the synchronization accuracy of four corners' operation within 10 mm and analyzed the wheel pressure and dynamic stiffness of the heightened quay crane, which, however, failed to perform a modal analysis of the metal structure via FEA. Using the hoisting method, Huang B. et al. [8] carried out a preliminary theoretical analysis on the dynamic stiffness of a heightened quay crane in the trolley travel direction and made a FEA comparison of dynamic stiffness among different structure-heightening schemes. An effective measure for improving the dynamic stiffness of a heightened quay crane in the trolley direction was derived but was inapplicable to the hydraulic jacking method. Hou R. et al. [9] proposed a plan to transform a double-lift quay crane into a single-lift one and demonstrated the stability of an entire quay crane after the transformation. However, their plan was aimed at transforming trolleys, which could not fulfill the loading and unloading requirements of larger container ships. Zhang W.F. [10] corrected the FEA model of a quay crane based on model substitution, which improved the efficiency and accuracy of model correction. However, the advantages and disadvantages of the two substitution models were indistinct with regard to the accuracy correction of the quay crane structure. Zhang B. [11] heightened the support columns by adopting a lifting strategy that added bilateral connecting beams to the support columns and using eight hydraulic lifting cylinders. Although the heightening modification process was expounded, no further simulation analysis was made on the safety performance of the heightened quay crane structure. Xu X.Z. et al. [12] built the crane FEA model using ANSYS software, which analyzed the first seven-order frequencies and mode shapes of the crane and conducted modal tests on the overall quay crane structure under environmental excitation. On the downside, the number of orders in the modal analysis was relatively small, and the stability analysis of the quay crane structure was insufficiently specific. Andrea Arena et al. [13] reported the research, optimization, and validation of semi-active control architecture for the load vibration control of container cranes and designed a fully 3D modeling method for the cranes, which included shock absorbers. Through a shaking table test on the 1/20 scale container crane, Nguyen Van Bac et al. [14] investigated the effects of different boundary condition models on the seismic response of container cranes, which offered a reference for container crane seismic research. However, the study was inapplicable to the metal structure of quay cranes after being heightened. Golovin Ievgen et al. [15] proposed a differential-based control strategy for large underactuated gantry cranes. Although the nonlinear stability control of the gantry cranes was deduced by distributed parameter modeling based on Hamilton's principle, the authors failed to analyze or verify the robustness of their proposed method. Abdullahi A.M. et al. [16] developed a novel control scheme for 3D bridge cranes with payload hoisting and persistent wind disturbance, which provided a guarantee for the precise positioning of the cranes. However, stability analysis on the crane metal structure was lacking. Gašić V et al. [17] developed a mathematical model of cranes by FEA combined with analytical method to obtain the crane structural response and relevant dynamic characteristics. The shortcoming of the study was that it focused on investigating the moving load problem in the moving trolley model but did not explore the stability of the whole crane. Schlott et al. [18] modeled a tower crane as a multi-body system and described the basic dynamic properties of the tower crane structure with fewer degrees of freedom. However, they failed to conduct a dynamic simulation or experimental analysis. Leszek et al. [19] conducted a numerical analysis on portable gantry cranes and evaluated the effects of changes in crane girder shape and loading force position on the equivalent stress generation of the crane girder. Although their findings provided a reference for enhancing the strength of gantry crane structures, these were inapplicable to quayside container cranes. Rauscher et al. [20] proposed a modal method for slewing control based on a distributed mass model, which enabled the payload stabilization and positioning of cranes with large jibs or powerful slewing drives. However, validation of their model is still required by experimental results.

The above studies focus on the heightening approach and 3D modeling of quay cranes, yet systematic simulation and analysis are lacking on the metal structure reliability of quay cranes after heightening modification. In particular, research concerning the static and dynamic characteristics of metal structures is even rarer. In this study, a method combining automatic hydraulic jacking and FEA is adopted. The overall height of the quay crane was increased by 6m without changing its mechanical structure and electrical circuit. After heightening modification, two more layers of containers could be loaded and unloaded. Next, a FEA model of the quay crane metal structure was created via ANSYS software, with which the static calculation and modal analysis were performed on the metal structure under typical operating conditions. The stress and displacement nephograms of the metal structure were compared, and the stress and deformation observations at various points were analyzed when the trolley was in different critical positions. The findings of this study provide an important basis for the heightening modification and safety performance assessment of quay cranes.

The remainder of this study is organized as follows. In Section 3, the process of quay crane heightening is described, the FEA model of the quay crane is built, and the FEA simulation and experimental analysis are conducted. In Section 4, stress and modal computations are analyzed by FEA, and the stress and displacement nephograms of the quay crane metal structure are obtained under different operating conditions. The last section draws relevant conclusions.

3. Methodology

3.1 Analysis of the quay crane heightening process

1) Relocation plan

Existing technical solutions for quay crane heightening inevitably encounter the problem of crane displacement. Owing to the complicated process and long construction period of quay crane heightening projects, any prolonged berth occupation is disallowed in the quay production operation. Thus, quay cranes are generally required to be relocated to the marginal berth areas for heightening modification. The following relocation plan was formulated after a pre-analysis and on-site survey.

As shown in Fig. 1, initially, all quay cranes on the right side of the to-be-heightened quay crane were moved to the right of the rearward position and the to-be-heightened quay crane was moved rearward. Next, all quay cranes were moved to the left of the rearward position and the to-be-heightened quay crane was moved back inside the runway. Afterwards, the to-be-heightened quay crane was relocated to the heightening position to prepare for heightening while the rest of the cranes resumed normal operation.

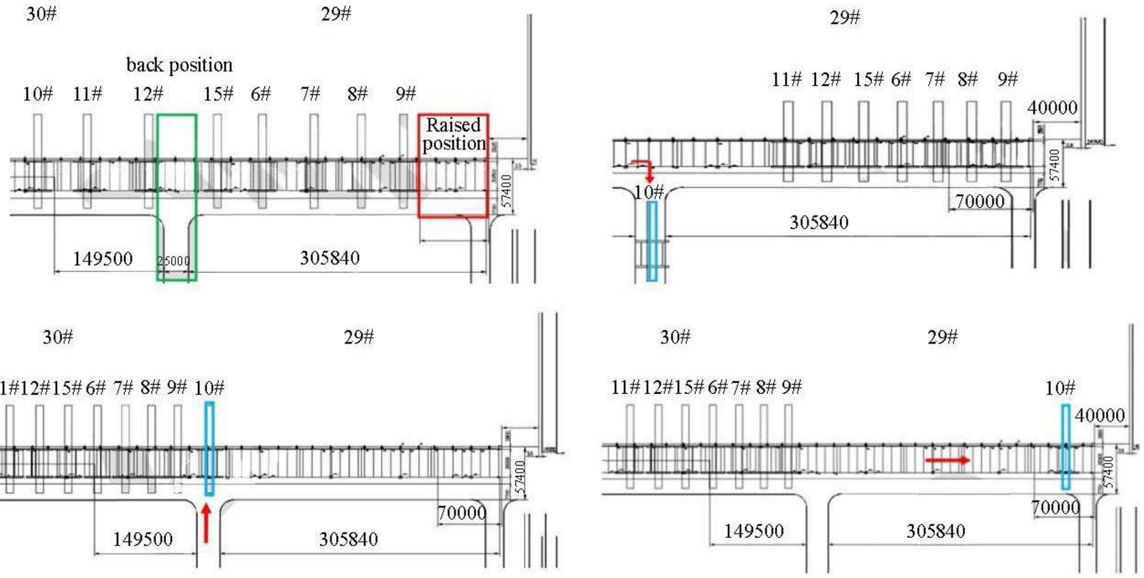


Fig. 1. Relocation scheme drawings

2) Quay crane modification principle
The Lianyungang Port Container Terminal organized technical personnel to increase the overall height of its 61t-55m quay crane by 6m. As shown in Fig. 2, the lower column part was heightened by 6m.

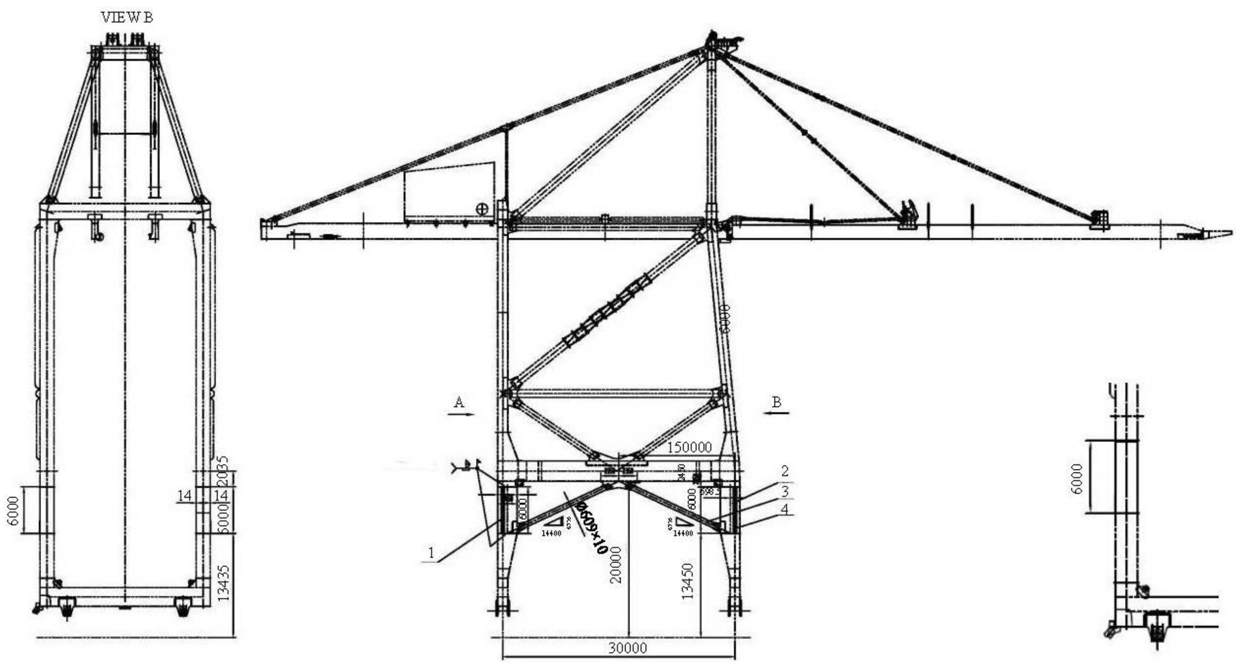


Fig. 2. Schematic of lower structure heightening

According to the actual situation of Lianyungang Port, hydraulic jacking method was adopted for heightening modification in this study, since the use of a floating crane would greatly affect the smooth entry and exit of ships and the loading/unloading operations at the port, whose rental price was relatively high as well. Specifically, a set of quay crane jacks were used and installed on the lower crossbeams of the door frame. The supporting beam and lower crossbeam were weld-connected, and local structural reinforcement was implemented. Four pairs of lifting brackets were arranged at the four corners, and hoisting was implemented via lifting crossbeams and column corbels. The lifting girder was arranged on the lifting brackets, and the lifting hydraulic cylinders were placed on the lifting girder. Figure 3 illustrates the specific arrangement.

3.2 FEA modeling of quay crane

As shown in Fig. 3, the metal structure of quay cranes often comprises a door frame, a ladder frame, a main girder, a tie rod system, and a door frame connection system [21]. In the case of the 61t-55m quay crane at Lianyungang Port, after heightening by 6m, its basic parameters were 55m outreach, 18m backreach, 30m main span, 28m width, 72m total height, 1250 t total weight, and Q345B steel material.

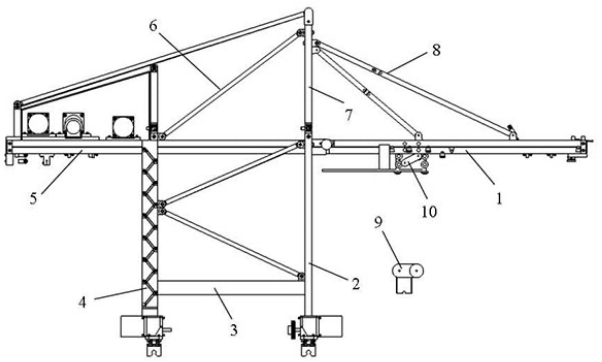


Fig. 3. Composition of the quay crane metal structure
1-Front girder 2-Seaside column 3-Door frame connecting crossbeam 4-Landside column and ladder 5-Rear girder 6-Rear tie rod 7-Portal gantry 8-Front tie rod 9-Spreader 10-Trolley

According to the actual size of the quay crane after heightening modification, parametric modeling was performed with Beam188 elements in ANSYS. The FEA model encompassed a total of 9,580 beam elements. The articulation between the front girder and the front tie rod was simulated with linkage elements [22]. Pre-processing and post-processing were both carried out in ANSYS, and the solving was accomplished by ANSYS/Block Lanczos. During the model simplification, unnecessary structures and holes could either be simplified into mass points or eliminated. After the crane structure model was imported into ANSYS, mid-surface extraction, geometry cleanup, material property creation, and meshing were performed without considering other objects. Finally, the nodes and elements were analyzed.

The steps were as follows: element selection – material property input – creation of beams, tubes, sectional areas and mass elements – creation of nodes and elements – element coupling – density adjustment – load calculation – application of constraints and loads [23]. The material of the quay crane structural members was Q345B plates, which had a density of 7.85 × 103 kg/m^3, elastic modulus of 2.1×1011 Pa, and a Poisson's ratio of 0.3. Figure 4 illustrates the FEA model of the whole crane structure.

(a) (b)

Fig. 4. Quay crane FEA model. (a) Metal structure geometry of the quay crane. (b) FEA model of the quay crane

3.3 Analysis of transient stress response

1) Load transient analysis

Calculations revealed that the vertical full load of the quay crane was 1,367,970N and its horizontal load was 124,662N.

Under normal circumstances, large structures like quay cranes are easily affected by wind load excitation and slamming during operation. Since the duration of such loads is not only shorter but also faster than the structural response, the structures continue free vibration after impact, which can even reach peak response. Calculations of the response by quasi-static analysis may result in large errors. The transient response analysis, on the other hand, can better reflect the actual results [24].

The dynamic response of a structure usually satisfies Formula (1), where P denotes the load vector and u denotes the dynamic response of the structure.

$$[M]\{\ddot{u}(t)\}+[B]\{\dot{u}(t)\}+[K]\{u(t)\}=\{P(t)\} \tag{1}$$

In this study, analysis was made by exploiting the central differencing scheme, which performed Taylor expansion on the dynamic response while disregarding the higher-order terms (exceeding second order). The compilation yields the following:

$$[A_1]\{u_{n+1}\}=[A_2]+[A_3]\{u_n\}+[A_4]\{u_{n-1}\} \tag{2}$$

Solving Formula (2) simply requires setting the initial u_0 and u_1. As the initial value, u_0 was set by the system, where u_1 is expressed as

$$\begin{cases} u_1=u_0+\Delta t\dot{u}_0+\dfrac{\Delta t^2}{2}\ddot{u}_0 \\ [M]\ddot{u}_0=P_0-[B]\dot{u}_0+[K]u_0 \end{cases} \tag{3}$$

2) Operating condition selection

Based on a combination of characteristics and operating experience of the quay crane, eight critical load positions requiring focused calculation are listed in Table 1. These positions were divided into eight operating conditions.

Table 1. Load position settings for the quay crane under various operating conditions

Condition	Load position	Condition	Load position
1	Maximum outreach position	5	Bottom position of seaside crossbeam
2	Midpoint between inner front tie rod hinge and maximum outreach position	6	Midpoint between landside crossbeam and seaside crossbeam
3	Hinge position of inner front tie rod	7	Bottom position of landside crossbeam
4	Midpoint between inner front tie rod hinge and seaside crossbeam	8	Maximum backreach position

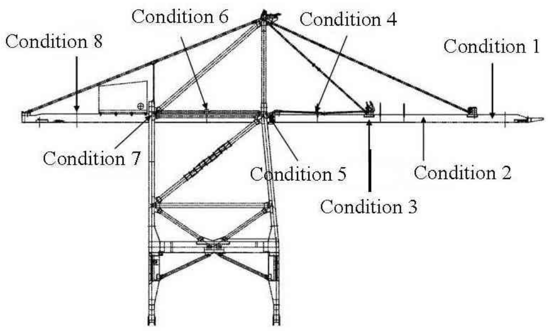


Fig. 5. Load application positions

3.4 Modal analysis of metal structure

1) Basic modal principles

Modes are the natural vibration characteristics of a structural system, each of which has specific natural frequency, damping ratio, and shape. When the structure vibrates freely while disregarding damping, its equation is as follows [25]:

$$[M]\{\ddot{u}\}+[K]\{u\}_i=\{0\} \tag{4}$$

Where $[M]$ is the mass matrix, $[K]$ is the stiffness matrix, $\{\ddot{u}\}$ is the acceleration vector, and $\{u\}$ is the displacement vector.

When harmonic vibration occurs, there is

$$u=U\sin\omega t \tag{5}$$

Where ω is the natural frequency of the structural vibration.

Substituting (5) into (4) yields

$$\left([K]\omega_i^2[M]\right)\{\phi_i\}=\{0\} \tag{6}$$

For modal analysis of a structure, its natural circumferential frequency and modal shape can both be obtained from the foregoing rectangular equation.

2) First N-order natural frequencies and modal shapes

During the modal analysis calculation, the parameters (i.e., density, plate thickness, gravitational acceleration, etc.) were set and automatically applied by ANSYS/Block Lanczos. The ANSYS/Block Lanczos solver is used to solve the first N-order constraint modes of the quay crane metal structure. Table 2 presents a list of the typical modes.

Table 2. Modal calculation results of the quay crane metal structure

Order	Frequency/HZ	Description
1	0.261	Overall forward tilt
2	0.417	Horizontal outward tilt of front and rear beam ends
4	1.085	Outward extension and overall downward movement of front tie rod
6	1.221	Upward movement and inward retraction of front tie rod
7	1.263	Upward movement and outward extension of front tie rod Downward movement of front girder
8	1.336	Positive Y axial movement and forward/backward horizontal movement of front tie rod
10	1.713	Extension of front and rear girders on both sides of horizontal plane, and movement of rear girder within horizontal plane
12	2.235	Bending of front and rear girders within horizontal plane
30	3.555	Downward bending and twisting of front girder around X axis

4 Result Analysis and Discussion

4.1 Analysis of stress calculation results

Structural stress calculations were performed with ANSYS solver according to the load values as well as the load positions listed in Table 1. Table 3 details the stress calculation results of the main components under various operating conditions.

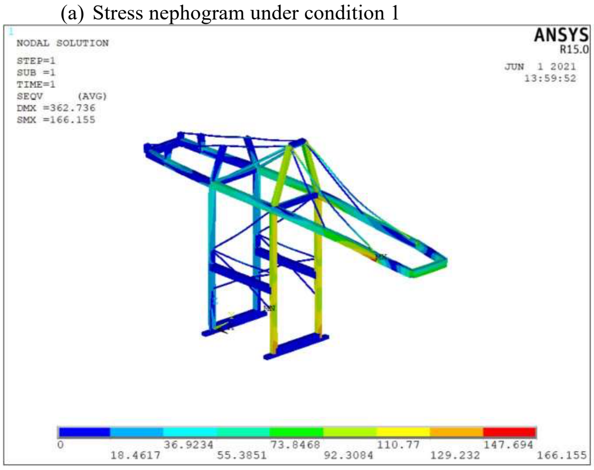
Different positions of the quay crane structure were analyzed under eight operating conditions, and the stress and displacement nephograms are displayed in Figure 6. Under condition 1, the maximum displacement of the quay crane structure was 362.74mm, which appeared at the front girder end. Meanwhile, the maximum stress was 166.15MPa, which was located at the hinge of the outer front tie rod. Under condition 2, the maximum displacement of the quay crane structure was 362.74mm, where the outer front tie rod was bent downward. Meanwhile, the maximum stress was 166.16MPa, which was located in the front half of the front girder. Under condition 3, the maximum displacement was 397.64mm, where the outer front tie rod was bent downward. Meanwhile, the maximum stress was 253.76MPa, which was located at the bottom crossbeam. Under condition 4, the maximum displacement was 57.63 mm, where the front girder was bent inward. The maximum stress was 118.42 MPa, which was located in the rear half of the front girder. Under condition 5, the maximum displacement was 47.87 mm, where the seaside column extended outward. The maximum stress was 244.49MPa, which was located in the middle of the seaside crossbeam. Under condition 6, the maximum displacement was 337 mm, where the outer front tie rod was concave. Meanwhile, the maximum stress was 183.84MPa, which was concentrated in the seaside column. Under condition 7, the maximum displacement was 330.23 mm, where the outer front tie rod was concave. The maximum stress was 306.19MPa, which was located at the bottom of landside crossbeam. Under condition 8, the maximum displacement was 318.95mm, and the maximum stress was 309.95MPa, which was located at the rear girder.

Table 3. Stress calculation results

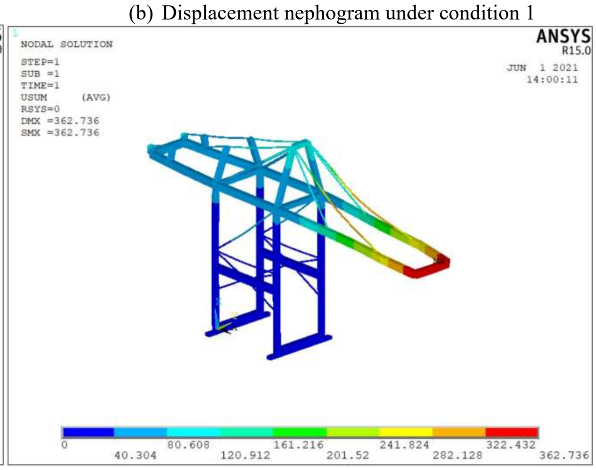
No.	Name	Maximum stress/MPa	Maximum displacement/mm	Material yield strength/MPa	Safety factor	Allowable stress/MPa
1	Front girder	269.98	352.63	345	1.5	230
2	Outer front tie rod	161.19	265.44			
3	Inner front tie rod	46.25	208.18			
4	Portal gantry	244.49	63.62			
5	Seaside column	224.76	1.12			
6	Landside column	195.19	0.58			
7	Inner rear tie rod	72.64	0.20			
8	Outer rear tie rod	108.81	0.41			
9	Rear girder	166.15	105.41			
10	Bottom crossbeam	108.92	20.55			

(a) Stress nephogram under condition 1

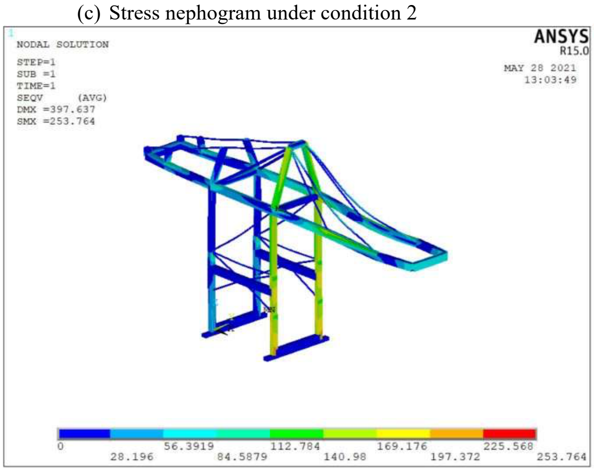
(b) Displacement nephogram under condition 1

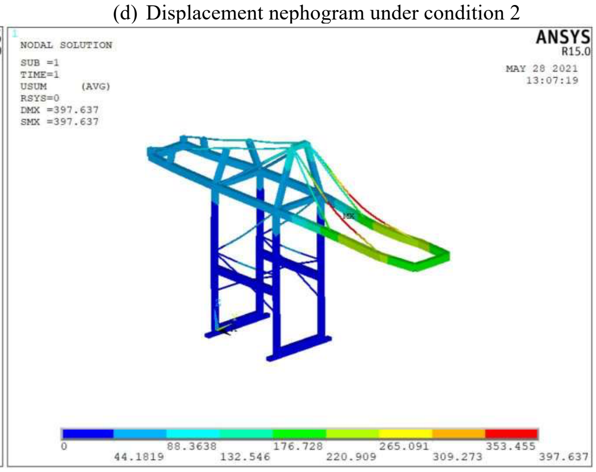


(c) Stress nephogram under condition 2



(d) Displacement nephogram under condition 2

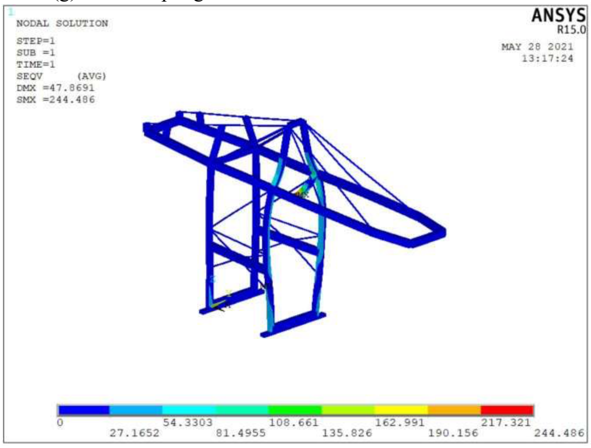




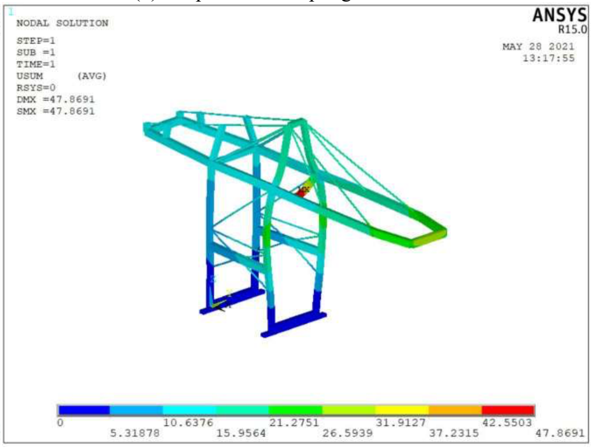
(e) Stress nephogram under condition 3 (f) Displacement nephogram under condition 3

(g) Stress nephogram under condition 4

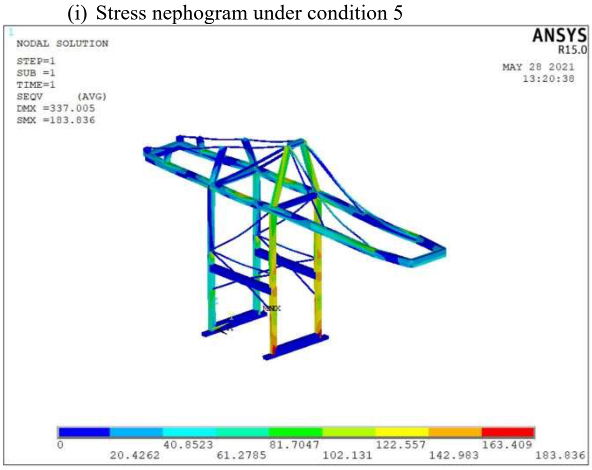
(h) Displacement nephogram under condition 4



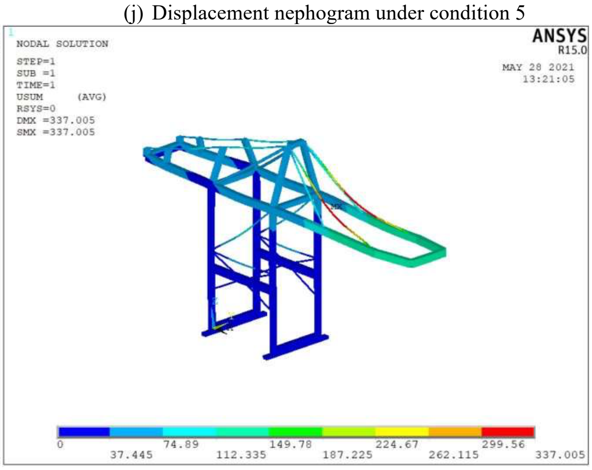
(i) Stress nephogram under condition 5



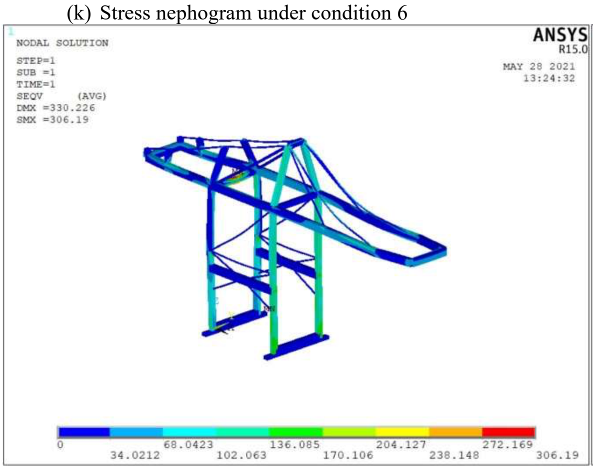
(j) Displacement nephogram under condition 5



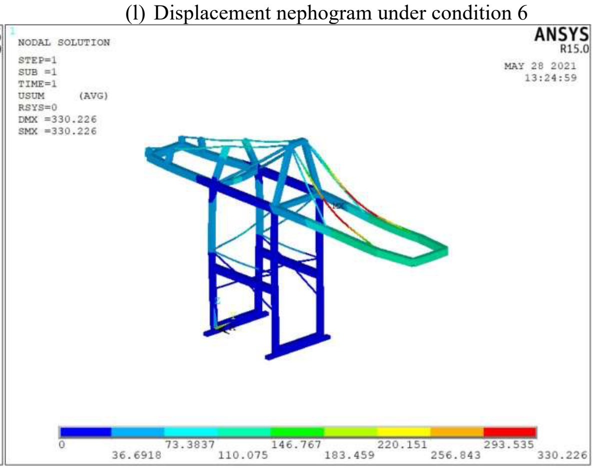
(k) Stress nephogram under condition 6



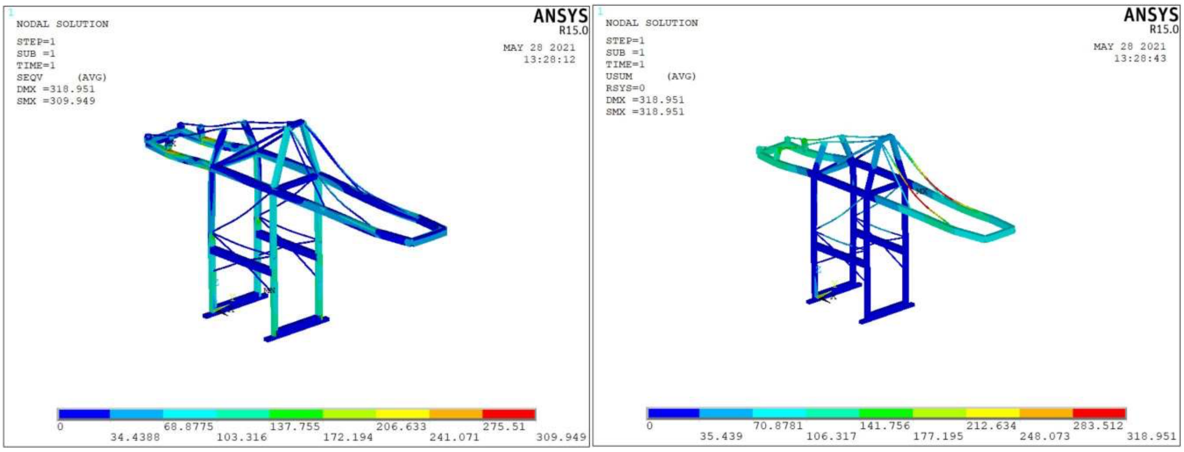
(l) Displacement nephogram under condition 6



(m) Stress nephogram under condition 7



(n) Displacement nephogram under condition 7



(o) Stress nephogram under condition 8 (p) Displacement nephogram under condition 8

Fig. 6. Stress and displacement nephograms under various operating conditions

In summary, under different operating conditions, the maximum stresses of the structure were all within the allowable stress range of the material. Except for the larger structural stress values of the front, rear girders, and outer front tie rod, the remaining components generally had smaller structural stresses. These results suggest that the structure of the quay crane is safe and reliable, and the proposed heightening method is reasonable and feasible.

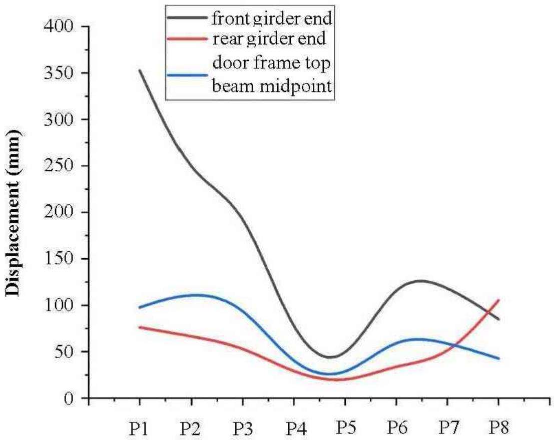


Fig. 7. Deformations upon load application at various positions

To better reflect the overall deformation of the quay crane metal structure, simulation analysis and calculation were performed to obtain the trolley deformation during travel from the maximum outreach to the maximum back reach (Fig. 7). The figure clearly shows that the deformation of the front girder front end underwent a process from upward warping to downward deformation while the rear girder underwent a process from downward deformation to upward warping. The deformation of the door frame structure was relatively gentle, and the stability of the whole crane was good.

4.2 Analysis of modal calculation results

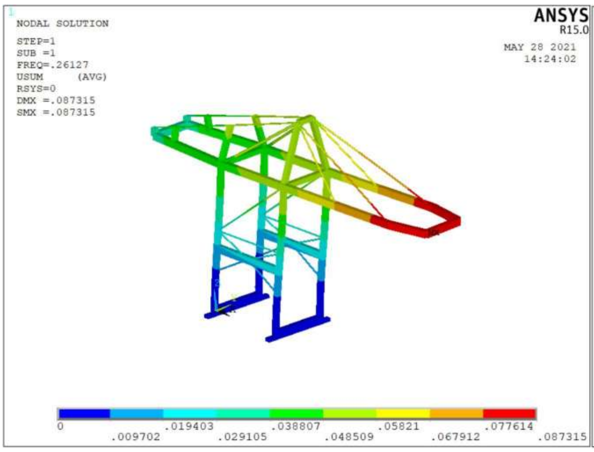
It is clear from Table 2 that when the frequency was 0.26–0.42Hz, the overall metal structure of the quay crane was twisted. When the frequency rose to 1.085–1.336Hz, bending and twisting occurred primarily at the front tie rod. At frequencies of 1.713–2.235Hz, bending and twisting occurred mainly at the front and rear girders. When the frequency further increased, the deformation evolved into bending or twisting of the front and rear girders as well as the overall metal structure. The vibration results of the metal structure in different frequency ranges can provide guidance for the operational safety and stability of the quay crane. Figure 8 displays its modal shapes.

As is clear from the 1st- and 2nd-order modal shape diagrams, the front girder underwent deformation within the horizontal plane. Nevertheless, the structure basically maintained its original shape, indicating that the seaside and landside columns can effectively resist vibration deformation. The 8th-order modal shape diagram showed that the front tie rod produced vertical bending deformation. The modal frequency was positively correlated with the stiffness of the vibration structure but inversely correlated with the mass, indicating preferable vertical stiffness of the front tie rod. The 10th- and 12th-order modal shape diagrams showed that the front girder and overall metal structure of the quay crane were bent along the girder axial direction. At this point, reasonable measures can be taken according to the theoretical calculations to avoid the resonance of the crane metal structure.

4.3 Experimental verification of quay crane heightening modification

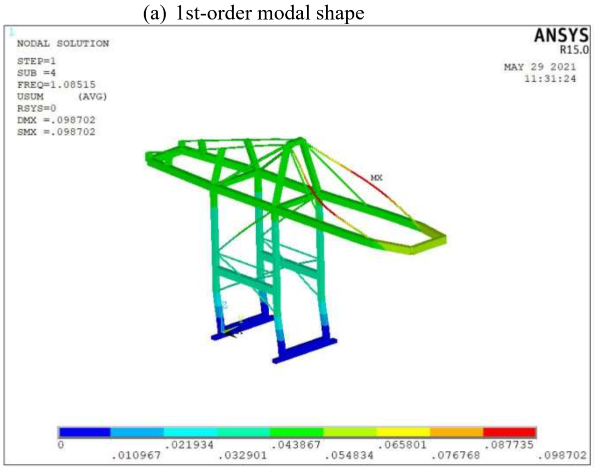
The above analyses indicated that Lianyungang Port successfully applied the hydraulic jacking method to the actual heightening of quay cranes, implementing heightening modification for four 61t-55m quay cranes. For each crane, one set of hydraulic jacks were installed on the lower crossbeam of the door frame. The supporting beam and lower crossbeam were weld-connected, and local structural reinforcement was implemented. Four pairs of lifting brackets were arranged at the four corners, whose effective lifting height was 6 m. Hoisting was implemented via lifting crossbeams and column corbels. The jacks were mainly in a box structure while the supporting structure was steel tubes. The lifting bracket bottoms and supporting beam were connected by bolts. The lifting girder was arranged on the lifting brackets, and the lifting hydraulic cylinders were placed on the lifting girder. Figure 9 illustrates the specific arrangement.

Experimental results showed that the structure of the heightened quay cranes is safe and reliable, which can meet the quayside loading and unloading requirements. The implementation of this project improves the loading/unloading capacities of the terminal, fulfills the operational demands of super-large ships, shortens the port berthing time of large ships, eliminates the risk of route loss, and meets the all-weather operational requirements of 3E-class container ships. Figure 10 presents the on-site construction photos.

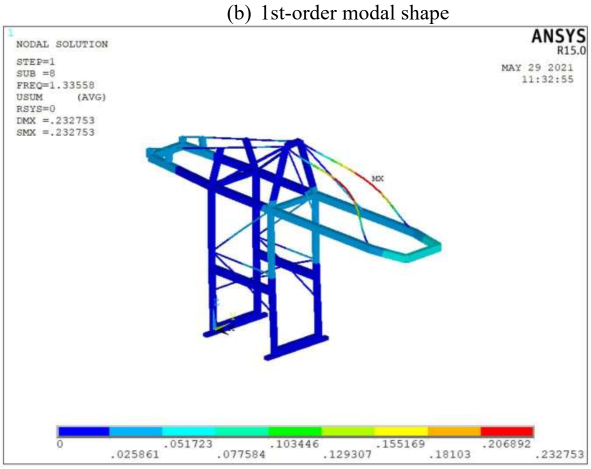


(a) 1st-order modal shape

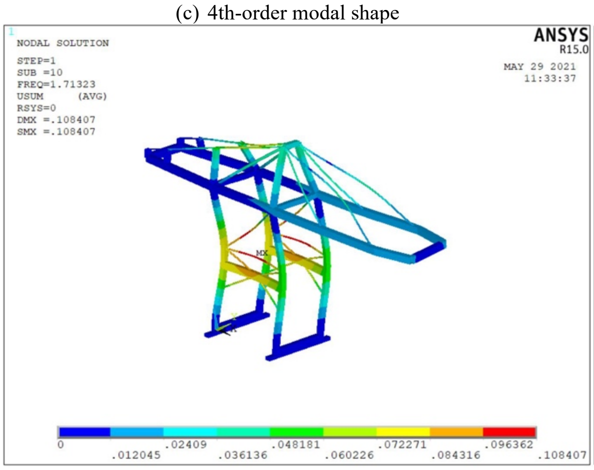
(b) 1st-order modal shape



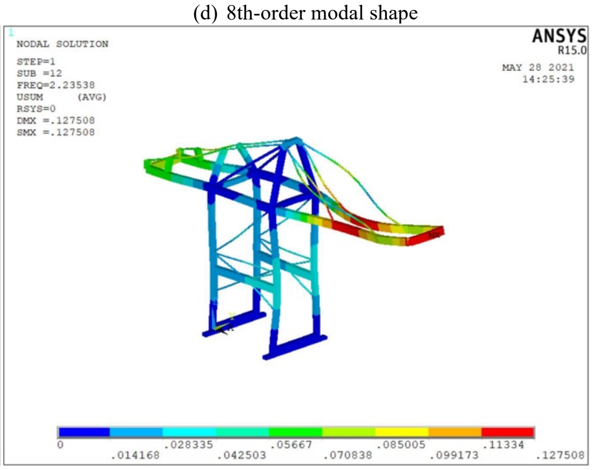
(c) 4th-order modal shape



(d) 8th-order modal shape



(e) 10th-order modal shape



(f) 12th-order modal shape

Fig. 8. First N-order modal shapes

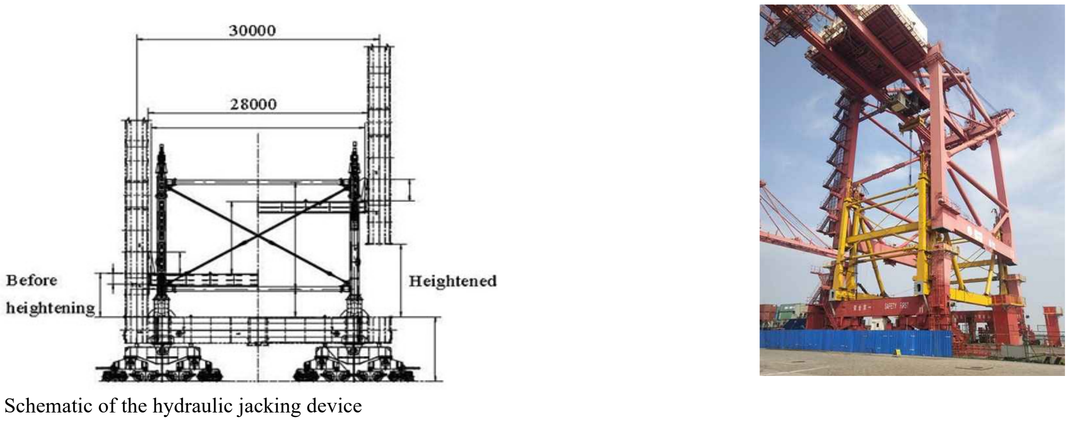


Fig. 9. Schematic of the hydraulic jacking device

Fig. 10. On-site photos of hydraulic jack arrangemen

5. Conclusions

Increasing the height of quay cranes is necessary to enable them to lift containers from 18,000 TEU ships. Such modification inevitably changes the metal structure of quay cranes and affects their reliability. The objectives of this study are to investigate the metal structure reliability after heightening modification of quay cranes and explore the rationality of the hydraulic jacking method. Beginning with FEA modeling of the quay crane, the stress, displacement, and mode of the crane metal structure were simulated and experimentally analyzed by adopting a method combining fully automatic hydraulic jacking and FEA. Finally, the following conclusions could be drawn:

(1) A FEA-based method is proposed to verify the rationality of the hydraulic jacking technique and allow the effective prediction of structural reliability after heightening modification of quay cranes.

(2) The maximum stress and displacement of quay cranes appear at the front and rear girders as well as the outer front tie rod. The modal frequency is directly proportional to the stiffness of the vibration structure and inversely proportional to the mass. The deformation of the door frame structure is gentle, and the stability of the whole crane is good.

(3) Two more layers of containers can be loaded and unloaded by the heightened quay cranes. The heightening modification cost for a single quay crane is only about 15% the cost of purchasing a new quay crane, which saves approximately 1 million USD. The heightening project improves the operational efficiency of the quay cranes and achieves good economic benefits.

In this study, a hydraulic jacking technique for quay crane heightening is proposed by combining engineering practices with simulation tests. The use of FEA allows for the correct determination of the crane's static and dynamic characteristics as well as the simulation of the crane operational process, which accords with on-site conditions and provides a certain reference for the heightening modification of quay cranes and the reliability assessment of metal structures. Given the lack of quay crane simulation analysis under the interferences of wheel pressure and wind load, these factors will be incorporated into the FEA model for correction in future study, with a view to improving the accuracy of structural stability determination for heightened quay cranes.

Acknowledgements
This work was supported by the 2020 Jiangsu Provincial Postgraduate Research and Innovation Program Project (KYCX20_2912).

References

1. Zhu, Q., "Technical practice of upgrade and transformation of terminal mooring capacity". *Port Operation*, 253(4), 2020, pp.8-10.
2. Tong, M., Shen,Y., "Research on coupled vibration of wheel-rail beam system in the high-speed quayside container crane". *Mechanics of Advanced Materials and Structures*, 27(17), 2020, pp. 1473-1482.
3. Sun, Y., Zhang, Q., Zeng, P., Bo, H., Mao, L., Qin, X., "Research on transformation scheme of large-scale quayside container crane for 3E 18000TEU container ship". *Hoisting and Conveying Machinery*, 476(10), 2014, pp.86-89.
4. Chen, X. , Wu, F., Tang, G., Hu, X., "Finite element analysis of doorframe structure of single oblique pole type in container crane". *Journal of Physics*,870(1), 2017, pp.12021.
5. Du, C., Wang, J. E., Mo, H., "Spatial pattern analysis of China container shipping network on complex theory". *Resources and Environment in the Yangtze Basin*, 25(2), 2016, pp.190-198.
6. Sun, Y., Qin, X., Zhou, Z., Zhang, Q., "Failure modes and effect analysis on fuzzy set theory of ship to shore container crane heightening". *Chinese Journal of Construction Machinery*, 16 (1), 2018, pp.1-5.
7. Lin, C., "Application and analysis of quay crane heightening technology". *China Ports*, 317(12)2019, pp.58-60.
8. Huang, B., Chen, D, D., "Research on improvement of dynamical stiffness of trolley in moving direction after heightening quayside container crane". *Port Operation*, 255(6), 2020, pp.18-22.
9. Hou R., Long, G., "Reconstruction scheme of double-lift quayside container crane trolley". *Intelligent City*, 107(10),2021, pp.131-132.
10. Zhang, W., Qin, X., Zhao, S., Pan, J., "Updating of finite element model of quayside container cranes based on the Kriging model". *Journal of Machine Design*, 363(1), 2020, pp. 48-52.
11. Zhang, B., "Heightening technology of double link beams of gantry and legs of quayside crane". *Port Science & Technology,* 156(2), 2019, pp. 3-6.
12. Xu, X., Zhang, X., Zhu, W., Gu, X., "Modal parameter identification of a quayside container crane based on data-driven stochastic subspace identification". *Journal of Vibration Engineering & Technologies,* 9(5), 2021, pp.1-20.
13. Andrea, A., Lacarbonara, W., Casalotti, A., "Payload oscillations control in harbor cranes via semi-active vibration absorbers: modeling, simulations and experimental results". *Procedia Engineering*, 199(9), 2017, pp.501-509.
14. Nguyen, V. B., Huh, J., Meisuh, B. K., Tran, Q. H., "Shake table testing for the seismic response of a container crane with uplift and derailment". *Applied Ocean Research*, 114(7), 2021, pp.102811.
15. Golovin I., Palis S., "Modeling and discrepancy based control of underactuated large gantry cranes". In: *21st International Federation of Automatic Control World Congress*, Berlin, Germany: Elsevier, 2020, pp.7783-7788.
16. Abdullahi, A., Mohamed, Z., Selamat, H., Pota, H. R., Abidin, M., Fasih, S. M., "Efficient control of a 3D overhead crane with simultaneous payload hoisting and wind disturbance: design, simulation and experiment". *Mechanical Systems and Signal Processing*, 145(1), 2020, pp.106893.

17. Gai, V., Zmi, N., Milovanevi, M., “Considerations of various moving load models in structural dynamics of large gantry cranes”. *Faculty of Mechanical Engineering Transactions*, 41(4), 2013, pp.311-316.
18. Schlott, P., Rauscher, F., Sawodny , O., “Modelling the structural dynamics of a tower crane”. In: *IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*, Banff, Canada: IEEE, 2016, pp.763-768.
19. Sowa, L., Skrzypczak, T., Kwiatoń, P., “The effect of the gantry crane beam cross section on the level of generated stresses”.In: *Machine Modelling and Simulations 2017*, Sklené Teplice, Slovak Republic: EDP Sciences, 2018, pp.02047.
20. Rauscher, F., Sawodny, O., “An Elastic Jib Model for the Slewing Control of Tower Cranes”. In: *20th International Federation of Automatic Control World Congress*, Berlin, Germany: Elsevier, 2017, pp.9796-9801.
21. Ling, J., “*Finite Element Analysis and Life Prediction Research on Quayside Container Crane*”. Master thesis of East China University of Science and Technology, China, 2015, pp.15-21.
22. Zhang, H., Li, M., Guo, Y., “A study on the lightweight of quayside container crane metal structure based on mode frequency and stiffness”. *Machinery Design & Manufacture*, 213(11), 2008, pp.109-111.
23. Han, J., “*Wind Tunnel Study on the WindLoad of Quayside Container Cranes*”. Master thesis of Tianjin University of Technology, China, 2020, pp.18-29.
24. Chen, Z., Yang, Q., Yu, D., Gui, H., Cong, P., “A method for transient slamming responses of the crossstructure of a trimaran based on grillage model”. *Journal of Ship Mechanics*, 217(11), 2021, pp.1498-1505.
25. Qi, P., “*Parametric Design and Fatigue Life Analysis of Quayside Container Crane's Steel Structure*”. Master Thesis of Lanzhou Jiaotong University, China, 2018, pp.42-53.