Integrated Design Optimization System of Supporting Structures for Tower Cranes

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***Abstract*—The supporting structure for a tower crane is crucial and its design is quite complicated due to multiple design considerations. At present, such structural design period for a tower crane in Hong Kong is time-consuming; final design is not optimal and material may be partly utilized; and the lack of professional design software causes the redundant calculation for design and scheme modifications. In order to solve the problems aforementioned, a design optimization system for the supporting structures of a tower crane had been established; design procedure and modules had been standardized and integrated with construction to take into account all kinds of tower crane types commonly used and their corresponding supporting structures including H-shaped steel beams and footings, respectively. The design optimization system can help engineers greatly speed up the design process and achieve cost effectiveness. In addition, standardization of the design process and modules will improve the design quality and structural safety.**

***Keywords*—tower crane, supporting structures, design optimization, modularization, standardization**

I. Introduction

Tower cranes are indispensable equipment in current construction and are widely used in civil construction, bridges, petrochemicals, power stations, aerospace, ports and other engineering construction. In 2020, the market held about 460,000 tower cranes in mainland China [1]. In Hong Kong, there are also hundreds of tower cranes in operation. With the widespread use of tower cranes, safety accidents related to tower cranes occur from time to time. In 2020, there were 72 tower crane-related safety accidents in mainland China [2]. In 2022, three tower crane-related safety accidents occurred in Hong Kong, all of which caused significant casualties and property losses.

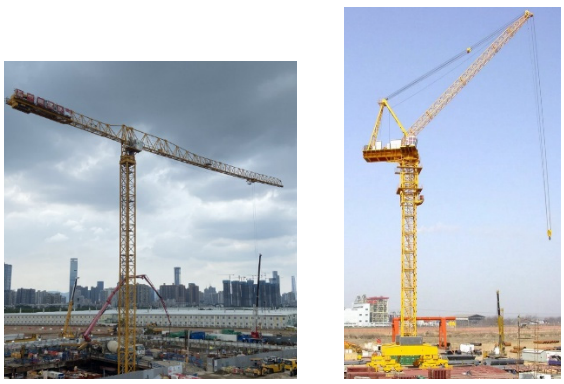
In order to ensure the safe operation of tower cranes, the safety of their supporting structures is very important. In Hong Kong, tower crane supporting structures are mostly designed by contractors. Designers usually use manual calculations or Excel spreadsheets to assist in calculations, which results in low design efficiency, non-standard design process, material waste, and sometimes safety hazards due to incomplete consideration. Therefore, studying to improve current design of tower crane supporting structures and even to optimize the structures is very valuable.

Novel systematic optimization techniques had been developed for elastic and inelastic structures under static and dynamic loadings and extensive optimization studies had been carried out [3–9].

Based on the commonly used tower crane models and design specifications in Hong Kong, this study sorts out and standardizes the design process of tower crane supporting structures, and builds an integrated design optimization system for tower crane supporting structures, and considers member optimization.

II. Design Prcedure of Tower Crane Supporting Structures

Tower cranes can be divided into fixed and traveling types according to their mobility, as shown in Fig. 1. The tower cranes commonly used in construction sites are fixed type. According to their connection status with the building, they can be divided into three working states: free-standing, attached and internal climbing, as shown in Fig. 2.



(a) Fixed type (b) Traveling type [10]

Fig. 1. Tower crane types (classified by traveling mechanism).

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If the maximum free-standing height specified in the tower crane manual meets the use requirements, there is no need to set up an attachment device or climb. And the tower crane is in the free-standing state. If the maximum free-standing height of the tower crane does not meet the use requirements, there are two ways to increase the height according to the location of the tower crane: first, the tower crane is installed outside the building, the height of the tower crane is increased by adding standard sections, and attachment devices are set to connect the tower body to the building, which is called the attached working state; second, the tower crane is installed inside the building and lifted by an internal climbing device, which is called the internal climbing working state.

In the free-standing working state, the tower body is a tall vertical cantilever truss under wind load. As a result, the tower body is subjected to a large bending moment at the bottom, which generates large axial forces in the legs. Generally, the supporting structure in this working state is subjected to larger forces than in other working states. Thus, this study focuses on the design of supporting structures for tower cranes in the free-standing state.

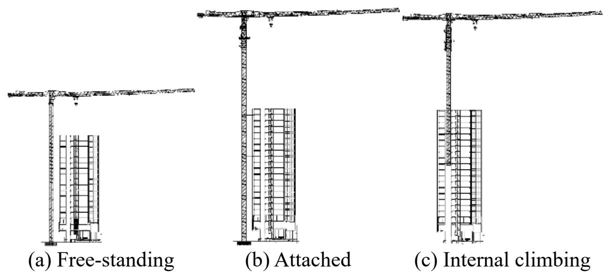


Fig. 2. Working status of tower cranes.

The design of the tower crane supporting structure can be mainly divided into the following steps.

A. Step 1: Selection of The Tower Crane Model

Based on transportation requirements such as lifting height, transportation distance, lifting weight, etc., the tower crane model, as well as the jib length and the mast height, can be determined. According to the tower crane model, the member size of the tower crane structure can be determined for subsequent calculation of internal forces under wind load and gravity. According to the statistics of tower cranes used in our company in the past 3 years, the usage ratio of 9 types of tower cranes exceeds 95%. A selection library has been established based on these 9 types of tower cranes.

B. Step 2: Calculation of Leg Forces

First, the design loads of the tower crane in both in-service and out-service states are calculated. The in-service loads mainly include the self-weight of the tower crane G_1, the weight of the hoisted object G_0, the wind load W_1, and the loads caused by the operation of the equipment such as the tower crane hoisting and slewing; the loads in the non-working state mainly include the self-weight of the tower crane G_1 and the wind load W_2. Then the leg forces at the bottom of the tower crane are calculated according to the design loads.

In fact, in the in-service state, the measured wind speed will not exceed the maximum wind speed specified in the tower crane manual, and the leg forces can be taken from the manual provided by the manufacturer. In the out-service state, due to the influence of topography, site elevation, and different wind pressures in different areas, the wind load needs to be calculated according to the wind load specifications in Hong Kong.

The leg forces calculated under the wind load in the out-service state and the gravity are combined, and the results are compared with the leg forces in the in-service state. By comparison, the larger forces are taken for the supporting structure design, including vertical force, horizontal force, and torque.

C. Step 3: Design of The Supporting Structure

The supporting structures of tower cranes mainly include the following types: pad footing, concrete beam foundation, pile cap, supporting steel beam, and supporting concrete beam, as shown in Fig. 3. Among them, concrete beam foundation and supporting concrete beams are rarely used in Hong Kong. Pile caps are generally part of the foundation of the main structure, and commercial finite element software is often used for modeling and calculation.

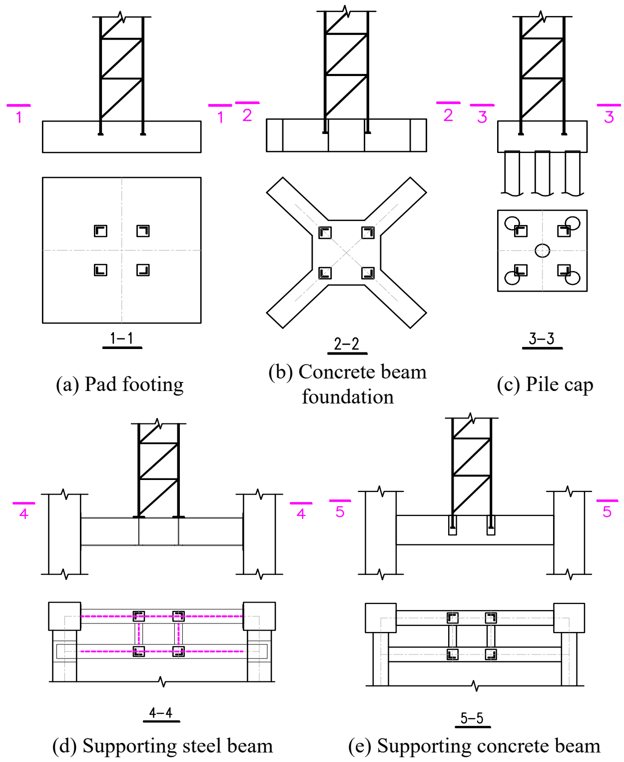


Fig. 3. Tower crane supporting structures.

The main items of the tower crane supporting structure design are listed in Table 1.

Through statistics on the tower crane supporting structures actually used by our company in the past three years, it was found that the pad footing and the supporting steel beam account for about 75% of the support structure. The design system established in this study is designed for these two most commonly used support structures.

TABLE I. MAIN CONTENTS OF THE SUPPORTING STRUCTURE DESIGN

Types of the supporting structures	Main design items
Pad footing	Checking of ground bearing capacity and foundation stability, bearing capacity design of pad footing, connection design between tower crane leg and foundation, etc.
Concrete beam foundation	Checking of ground bearing capacity and foundation stability, bearing capacity design of beam foundation, connection design between tower crane leg and foundation, etc.
Pile cap	Calculation of single pile bearing capacity, pile layout, design of bearing capacity for pile caps, connection design between tower crane leg and pile cap, etc.
Supporting steel beam	Supporting beam layout, steel beam bearing capacity design, steel beam deflection checking, connection design, etc.
Supporting concrete beam	Supporting beam layout, concrete beam bearing capacity design, connection design, etc.

D. *Step 4: Review of Main Structure*

If the supporting beams are used as the tower crane supporting structure, the main structure components connected to the supporting beams must also be reviewed. The reaction forces of the supporting beams are usually applied to the main structure calculation model for checking.

The design flow chart of the tower crane supporting structure is shown in Fig. 4.

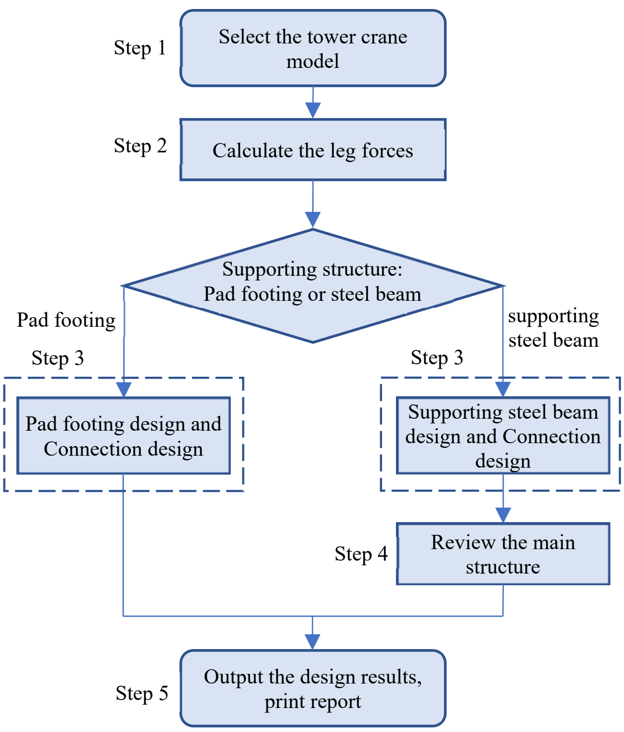


Fig. 4. Design flow chart of the tower crane supporting structure.

E. *Step 5: Output of Design Results*

After the design is completed, the calculation report needs to be compiled for review, archiving, etc.

III. DESIGN OPTIMIZATION FOR SUPPORTING STRUCTURE

An automatic optimization function is embedded in step 3 (supporting structure design) shown in Fig. 5 to obtain the component size with the minimum material consumption that meets the design requirements. For the pad footing and supporting steel beam, the design optimization process is as follows:

A. *Design Optimization of Pad Footing*

As shown in Fig. 5, the design optimization process of pad footing is presented as follows:

(1) Set the initial footing dimensions,

(2) Check the ground bearing capacity,

(3) Check the foundation stability,

(4) Bearing capacity design, including bending, shear, and punching shear resistance,

(5) If all the verifications are passed, the design will terminate; otherwise, the foundation dimensions are adjusted and the next design step is carried out until all verifications are passed.

According to the data statistics of the past design cases, the footing plane is set to a square with an initial thickness of 0.7m. The footing side length is set to 3 times the footing thickness plus the mast width of the tower crane. The step size for increasing thickness is 0.1m, and the step size for increasing side length is 0.3m.

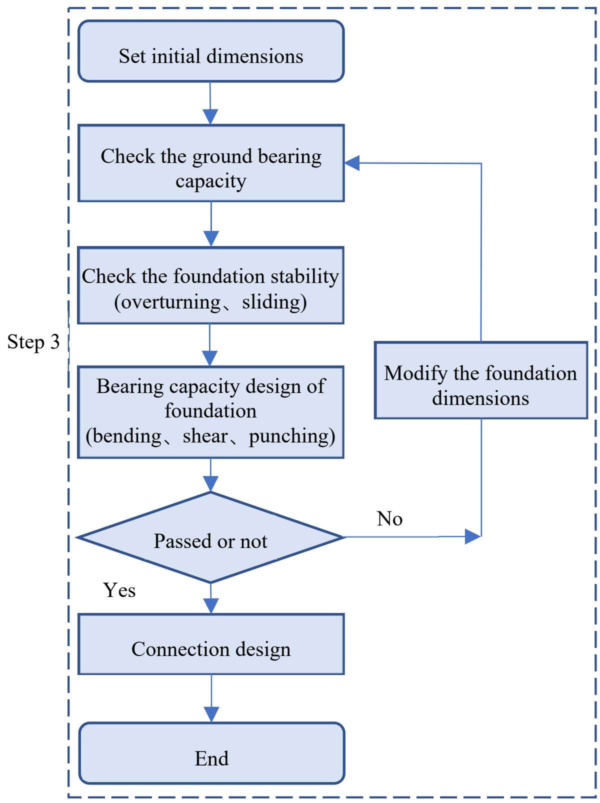


Fig. 5. Flow chart of design optimization for pad footing.

B. *Design Optimization of Supporting Steel Beam*

As shown in Fig. 6, the design optimization process for supporting steel beams is as follows:

(1) Set the initial beam section. The steel beam section is taken from the UB and UC sections in the British standard BS4: Part 1:1993. The H-shaped steel sections in the section library are sorted by section height and section area. The initial section of the steel beam is set to a light-weight section,

(2) Perform plate width-thickness ratio calculation, section classification, shear resistance checking, bending resistance checking, tension-bending combination checking, compression-bending combination checking, and deflection checking in sequence,

(3) If all the aforementioned design checks pass, the beam design will terminate; otherwise, the beam section will be adjusted and the next design step will be carried out until all verifications are passed.

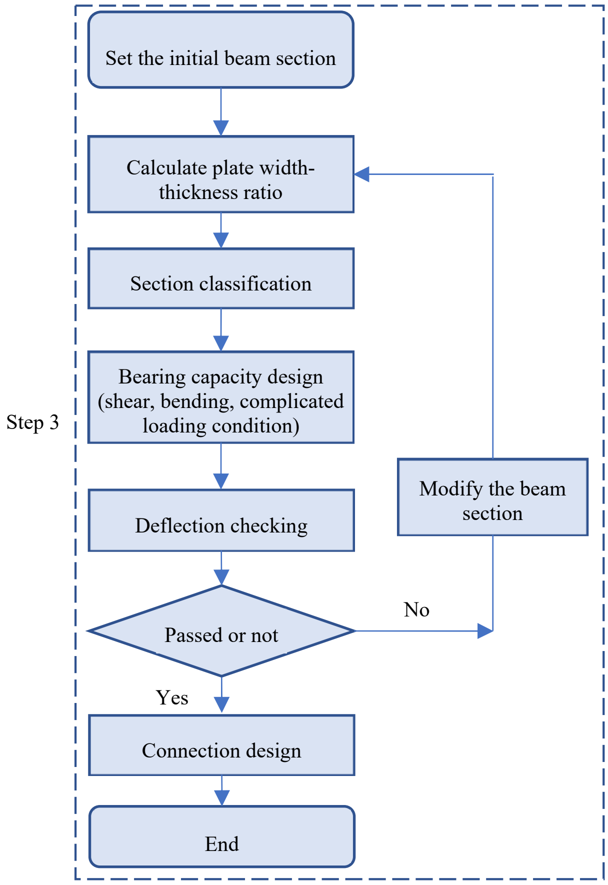


Fig. 6. Flow chart of design optimization for supporting steel beam.

IV. Standard Module for Tower Crane Supporting Structure Design and Optimization

Based on the design optimization process of the tower crane supporting structure, the following standard modules are developed:

(1) Module 1: determination of tower crane model and calculation of leg forces,

(2) Module 2: pad footing design optimization,

(3) Module 3: supporting steel beam design optimization.

The calculation function of each design module is realized by combining Excel spreadsheets with VBA programming. The advantages are:

(1) Excel spreadsheets are widely used and engineers are familiar with them. Excel has a large number of built-in functions and is simple and easy to use;

(2) VBA programming based on Excel can realize more complex functions such as automated data transmission, conditional judgment, loop control, etc., and is easy to learn and master;

(3) Excel spreadsheets are WYSIWYG, which is convenient for setting output formats and printing calculation reports.

Although VBA has weaknesses such as slow execution speed, weak error handling function, and poor cross-version compatibility, its adverse effects can be effectively reduced by optimizing code logic, unifying software versions, and strictly controlling data formats.

After completing the design optimization of the tower crane supporting structure, the main structure will be reviewed if it is required, and the checking report will be combined with the supporting structure design report to form the final design report.

V. Integrated Design Optimization System

For the convenience of user use and maintenance and upgrading by developers, a three-layer software architecture of B/S (Browser/Server) is adopted (as shown in Fig. 7). Based on the VBA combined Excel spreadsheet as the backend calculation module, the browser page as the front-end display and operation platform, and the JSON format process definition file, an integrated design optimization system for tower crane supporting structures is built. Users can use it by logging in to the browser page through networked personal computers, smartphones, and other devices. After the design is completed, the calculation report in PDF format can be exported for review and archiving.

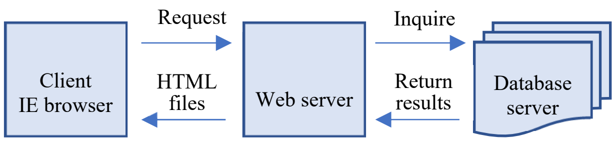


Fig. 7. The three layers of B/S architecture.

VI. Design Optimization Cases

Using the design optimization system built above, the supporting structure of a tower crane used in an actual project is redesigned. The design parameters are as follows:

(1) Model: Yongmao-STT293

(2) Jib length: 40m

(3) Hook height: 49.24m

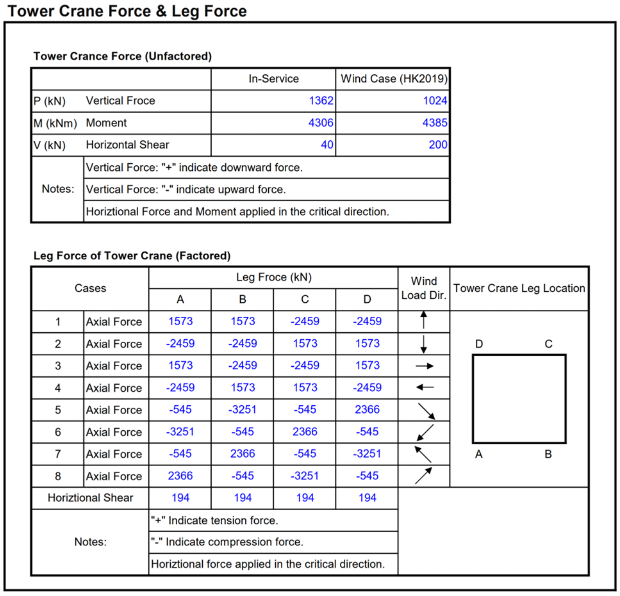
(4) Elevation of the tower crane bottom relative to ground: 0.00m

(5) Wind load topography factor: 1.0

(6) Wind load reduction coefficient of temporary structure: 1.0

The calculation results of the leg forces are shown in Fig. 8.

The design processes of pad footing and supporting steel beam are shown below.


Tower Crane Force & Leg Force

Tower Crance Force (Unfactored)

		In-Service	Wind Case (HK2019)
P (kN)	Vertical Froce	1362	1024
M (kNm)	Moment	4306	4385
V (kN)	Horizontal Shear	40	200
Notes:	Vertical Force: "+" indicate downward force.		
	Vertical Force: "-" indicate upward force.		
	Horiztional Force and Moment applied in the critical direction.		

Leg Force of Tower Crane (Factored)

Cases		Leg Froce (kN) A	B	C	D
1	Axial Force	1573	1573	-2459	-2459
2	Axial Force	-2459	-2459	1573	1573
3	Axial Force	1573	-2459	-2459	1573
4	Axial Force	-2459	1573	1573	-2459
5	Axial Force	-545	-3251	-545	2366
6	Axial Force	-3251	-545	2366	-545
7	Axial Force	-545	2366	-545	-3251
8	Axial Force	2366	-545	-3251	-545
Horiztional Shear		194	194	194	194
Notes:		"+" Indicate tension force.			
		"-" Indicate compression force.			
		Horiztional force applied in the critical direction.			

Fig. 8. Output interface of tower crane leg forces.

A. Pad Footing

The design parameters are as follows:

(1) Concrete strength grade: C45,
(2) Yield strength of rebar: 500MPa,
(3) Initial thickness of pad footing: 0.7m,
(4) Initial side length of pad footing: 4.1m,
(5) Footing base level: -1.5,
(6) Ground level: 0.0,
(7) Design water level: -2.0,
(8) Allowable bearing pressure of ground: 120kPa.

By the design optimization, the final footing side length is 8.3m, the thickness is 2.1m, and T32-200 is provided for flexural rebar. The design results are listed in Table II. The concrete consumption is 144.7 m^3, while the steel quantity is 8.7 tons.

TABLE II. THE DESIGN RESULTS OUTPUT OF PAD FOOTING

Design results	Allowable bearing pressure check	Overturning check	Sliding check	Bending capacity check	Shear & punching shear check
Ratio	0.99	0.37	0.18	0.69	0.94
Status	OK	OK	OK	OK	No shear links required

The variation curves of foundation pressure and safety factor against overturning during the optimization process are plotted as shown in Fig. 9. A total of 15 iterative calculations were performed. As the foundation size gradually increased, the foundation pressure gradually decreased, and the safety factor against overturning gradually increased. The final calculated maximum foundation pressure was 118 kPa, and the safety factor against overturning was 4.0.

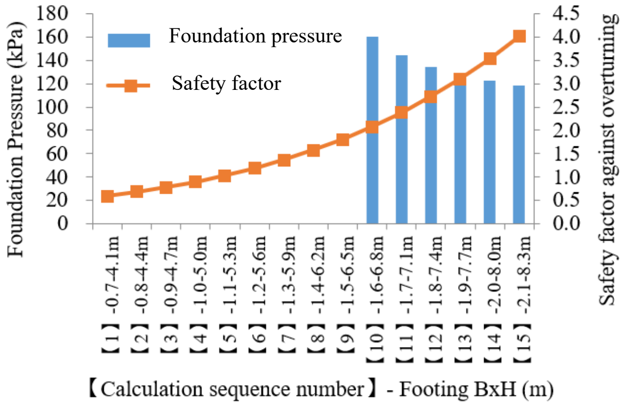


Fig. 9. Design results of pad footing during the optimization process.

B. Supporting Steel Beam

As shown in Fig. 10, the design parameters of the supporting steel beam are as follows:

(1) Steel strength grade: S355,
(2) Initial steel section: UB-533x210x82,
(3) Span of supporting steel beam: 5.0m,
(4) Positioning dimensions of tower crane legs: a=1.5m, b=2.0m, c=1.5m.

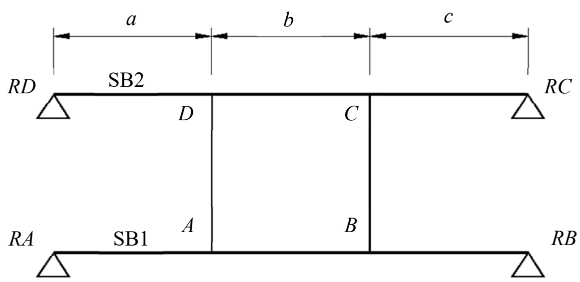


Fig. 10. Layout Plan of supporting steel beams.

By design optimization, the final section of the supporting steel beam is UB-1016×305×249. The design results are listed in Table III. The steel consumption is 2.0 tons.

TABLE III. THE DESIGN RESULTS OUTPUT OF THE SUPPORTING STEEL BEAM.

Design results	$\frac{V_x}{V_{cx}}$	$\frac{V_y}{V_{cy}}$	$\frac{M_x}{M_{cx}}$	$\frac{M_y}{M_{cy}}$	$\frac{m_{LT}M_x}{M_b}$	$\frac{F_c}{P_c}$	Comb. Comp.	Comb. Tension
Ratio	0.74	0.05	0.66	0.25	0.61	0.01	0.76	0.92
Status	OK	OK	OK	OK	OK	OK	OK	OK

The variation curves of the stress ratio and self-weight of the beam during the optimization process are plotted as shown in Fig. 11. A total of 27 iterative calculations were performed. The final section of the supporting steel beam is UB-1016×305×249, and the stress ratio was 0.92.

C. Comparison of Design Efficiency

After the design optimization is completed, a design report can be automatically generated. When the design conditions have been determined, it usually takes about one week for the designer to complete a design report for a tower crane supporting structure. Using the design optimization system proposed in this study, it only takes about 10 minutes, greatly shorten the design circle and obtaining support structures with optimized material usage, which can output standardized design reports.

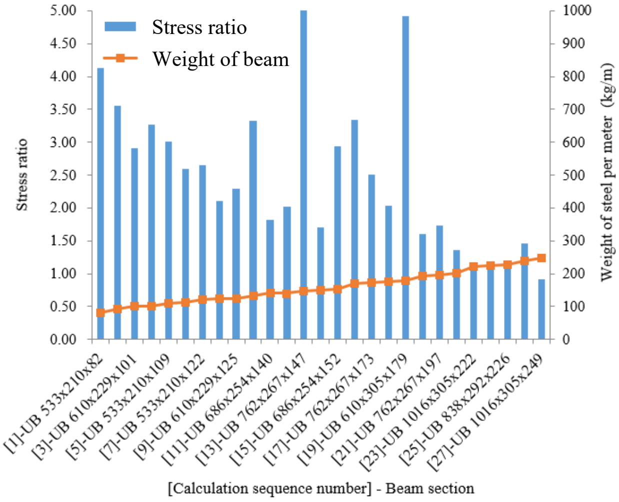


Fig. 11. Design results of steel beam during the optimization process.

VII. Conclusions

First, the design modules of supporting structures for tower cranes had been standardized and design optimization had been established and developed.

Second, using B/S software, an integrated design optimization system of supporting structure for the tower crane had been built by combining Excel spreadsheets with VBA programming as the back-end calculation module and a browser page as the front-end display and operation platform.

Third, two case studies were presented to demonstrate the significance and efficiency of the design optimization system.

The application in multiple actual projects in Hong Kong show that this system can effectively improve the design quality, and the safety, practicality and cost-efficiency. In addition, this system fills the gap of the lack of design software for tower crane-supporting structures in Hong Kong, which has practical significance and broad application prospects. The research methodology in this paper can also provide a reference and value for solving similar problems.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All authors conducted the research; Xiao Kang Zou, Yang Zhang wrote the paper; all authors had approved the final version.

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