Research on Safety Evaluation of Quayside Container Crane Metal Structure Based on 04-FCE

Mengya Zhang¹, Chensheng Huang¹, Kun Chen*, Jin Liu², Yan Gan¹, Jianyu Zhao³

¹School of logistics engineering, Wuhan University of Technology
²China Merchants Hoi Tung Trading Company Limited
³GuangZhou Port Company Limited

* kmno40311@163.com School of logistics engineering, Wuhan University of Technology

Abstract. In order to ensure the safety of quayside container crane in service and improve the port safety management level, from the engineering practice, according to the composition of the quayside container crane metal structure of six parts: the front girders, the rear girders, the beams, the trapezoidal frame, the tie rods, the columns, the factors that potentially have influence on the safety of the metal structure are researched, and the safety evaluation index system is built. The dimensionless algorithm of evaluation index is optimized emphatically. For the first time, the "0-4" evaluation method is used to calculate the weight value in the evaluation algorithm, and the 04-FCE evaluation method which combine the "0-4" scoring method and fuzzy comprehensive evaluation is proposed. The safety level and evaluation conclusion of the quayside container crane metal structure are determined, the suggestions for reducing the risk are given, and the rationality analysis is carried out through an example at last.

1. Introduction
With the construction of “the Belt and Road” and the rapid development of the world economy, the throughput of container ports increases sharply. As one of the most common container lifting equipment in ports, the number and frequency of use of quayside container crane are increasing, which puts forward higher requirements for their safety performance [1]. At present, the wharf safety accidents caused by quayside container crane account for about 30% [2]. The most serious accidents are caused by the faults and failures of metal structures, which cause enormous personal injury and economic losses to a large extent. Safety assessment and grade assessment of the metal structure of the quayside container crane can find the hidden safety risks in the structure as early as possible and timely dispose by means of scrapping, maintenance and inspection [3], which can effectively avoid the safety accidents caused by the failure of the metal structure of the quayside container crane.

At present, there are many theoretical methods for crane safety assessment, such as neural network evaluation method [4], grey comprehensive evaluation method [5], Fisher discriminant method [6], unascertained measurement theory [7], fuzzy comprehensive evaluation method [8], expert system method [9]. However, the accuracy of existing safety evaluation methods is greatly affected by the level of experts or the number of training samples. The data reflected in special cases are not true, which makes the robustness of the evaluation system inadequate. Moreover, the safety evaluation of crane is still at the theoretical level, and the practical application level is still shallow. Therefore, it is necessary
to establish a practical evaluation method of quayside container crane from the perspective of effectiveness, reliability and universality. For the first time, the 0-4 scoring method and the fuzzy comprehensive evaluation method are integrated in the safety evaluation study of quayside container crane metal structure, which is simple to operate and practical, providing strong support for the safety management of port.

2. The safety evaluation index system of quayside container crane metal structure is established

According to the design principle and engineering practice of quayside container crane, firstly, the factors affecting the safety of quayside container crane metal structure, such as strength, rigidity, stability, cracks, corrosion and maintenance, are analyzed and evaluated. Then, according to the analytic hierarchy process, the quayside container crane is divided into 6 subsystems: front girder, back girder, beam, trapezoidal frame, tie rod, and column. The single-factor analysis is carried out on them respectively. Finally, the safety evaluation index system of quayside container crane metal structure is constructed.

2.1 Analyze the influencing factors and select evaluation indexes

According to GB/T3811-2008 “Crane Design Code”, GB/T5905-2011 “Crane Test Code and Procedure”, GB6067.1-2010 “Crane Safety Regulations Part 1: General Provisions” [10], GB6067.5-2014 “Crane Safety Regulations Part 5: Bridge and Portal Crane”, GT/B17495-2009 “Port Gantry Crane”, “Crane Metal Structure”, etc, the factors affecting the safety of crane metal structure should be considered from two perspectives. From the design point of view, the influencing factors include strength, rigidity, stability, cracks, corrosion and deformation and so on. From the fault point of view, the influencing factors include cracks, corrosion, deformation, maintenance and so on. After analysis, for quayside container crane, the overall stability of the beam has met the safety criteria in the design stage, and the overall stability index and strength index are reflected by stress, while the partial stability is reflected in the deformation index. Therefore, the stability index is not used as an Independent evaluation index in the safety evaluation index system. Therefore, strength, rigidity, crack, corrosion, deformation and maintenance are selected as evaluation indexes.

2.2 Safety Evaluation Index System of Quayside container crane Structure

The safety evaluation index system of quayside container crane metal structure is divided into whole machine layer, subsystem layer and single factor layer. Through the evaluation results of several subsystems, the structural safety of the whole machine can be evaluated comprehensively. The evaluation of the subsystem is embodied by six indicators: strength, rigidity, crack, corrosion, deformation and maintenance.

The metal structure of quayside container crane is mainly composed of front girder, rear girder, cross beam, trapezoidal frame, column and tie rod. Because some factors have little influence on the safety of metal structures in some subsystems, the rigidity factors in the column subsystem do not participate in the safety evaluation, and the rigidity and deformation factors in the tie rod subsystem do not participate in the safety evaluation.

3. Establishment of safety evaluation model for metal structure of quayside container crane based on 04-FCE

To evaluate the safety of metal structure of quayside container crane, firstly, dimensionless optimization of evaluation index is carried out according to the actual situation. Then, safety evaluation model is established by 04-FCE evaluation method to determine the safety grade and evaluation conclusion of quayside container crane structure. Finally, corresponding suggestions are given to reduce the safety risk.

3.1 Determination of Evaluation Value

The safety evaluation indexes of quayside container crane metal structure include strength, rigidity,
crack, deformation, corrosion and maintenance. Because these dimensions are different, dimensionless treatment is needed before the calculation of fuzzy evaluation can be carried out.

The calculation of evaluation index value is divided into two steps: ① measurement of state value of single factor evaluation index; ② routinely dimensionless processing of state value of each index, which makes the range of value of index data unified, are all in [0, 1].

3.2 Determining the Weight of Evaluation Index

The "0-4" scoring method is used to evaluate the indexes involved in the safety evaluation of metal structures of quayside container crane, which is used to determine the weight of the indexes. "0-4" score can be scored by comparing important levels of two indicators in the evaluation index system by technicians.

The final weight of the index is expressed as the ratio of the score of one index to the total score of all indexes.

3.3 Establishment of Fuzzy Relation Matrix

Fuzzy evaluation includes four basic elements: evaluation result set (V), weight set (W), index set (U), fuzzy relation matrix (R): V includes all possible evaluation results of the object; W element is the weight of each index to the result; U is the set of evaluation indexes; R is the link of U and V, reflecting the relationship between evaluation index and evaluation result. The fuzzy relation matrix with n evaluation indexes and m evaluation results can be expressed as follows:

\[
R = \begin{bmatrix}
R_{11} & R_{12} & \cdots & R_{1m} \\
R_{21} & R_{22} & \cdots & R_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
R_{n1} & R_{n2} & \cdots & R_{nm}
\end{bmatrix}
\]

(1)

In existing researches, the determination of \(r_{ij}\) is usually made by Delphi, and the results are largely dependent on the subjective judgment of scoring experts. The evaluation results depend on the level of experts to a large extent, which is easy to produce deviation, not conducive to the operation of ordinary technical personnel, and not strong in the practical application of ports. In this study, the "distance normalization" method is adopted to determine the membership degree of evaluation value, which is simple and accurate. The method is as follows:

1. Let \(P=\{P_1, P_2, \ldots P_8\}\) is the midpoint of eight evaluation result sets, namely:
   \[P=\{6.25, 18.75, 31.25, 43.75, 56.25, 68.75, 81.25, 93.75\}\]

2. Judging the grade \(V_i\) of the evaluation result in which the evaluation value \(S_i\) falls;

3. Find the distance \(D_i\) between \(S_i\) and the corresponding midpoint \(P_i\) of \(V_i\), that is:
   \[D_i = |S_i - P_i|\]

4. Find the midpoint \(P_j\) of the nearest evaluation result set \(V_j\) from \(S_i\), and find the distance \(D_j\) between \(S_j\) and \(P_j\), that is:
   \[D_j = |S_j - P_j|\]

5. Find the reciprocal of \(D_i\) and \(D_j\), then normalize the results, we can get the membership degree of \(S_i\) in \(V_i\) and \(V_j\), and the membership degree of \(S_i\) in other intervals is 0.

Compared with the results obtained by Delphi method, the average error of this method and Delphi method is 0.68%, and the maximum error is 1.6%. Therefore, this method can replace Delphi method.

3.4 Fuzzy Comprehensive Evaluation

According to the multiplication operation of the fuzzy matrix, the fuzzy evaluation set can be expressed as \(B=\{B_1, B_2, \ldots B_m\}\), the fuzzy evaluation set \(B\) is calculated according to the following formula:

That is to say:
In this study, the weighted average method is adopted to solve the final evaluation result \( v \):

\[
B = W \times R
\]  
\[
v = \frac{\sum_{i=1}^{m} b_i v_i}{\sum_{j=1}^{m} b_j} \times 100
\]

The fuzzy comprehensive evaluation method is used for multistage evaluation, and the evaluation result \( v \) of the whole machine structure is obtained. 0-100 is equally divided into 8 intervals to form the safety level of \( v_1 \) to \( v_8 \) whole machine structure. Each evaluation value has a corresponding result state description:

- **V1**: when \( 0 \leq v \leq 12.5 \), the structure state of the whole machine is extremely poor, and relevant structural parts and even the whole machine should be scrapped;
- **V2**: when \( 12.5 < v \leq 25 \), the whole machine is in poor structural condition and must be immediately shut down for comprehensive overhaul;
- **V3**: when \( 25 < v \leq 37.5 \), the machine structure is not good, must be shut down for maintenance;
- **V4**: when \( 37.5 < v \leq 50 \), the overall structure has serious safety risks, it is necessary to develop the overall maintenance program and load reduction use;
- **V5**: when \( 50 < v \leq 62.5 \), there are many structural faults of the whole machine, so the maintenance scheme of the whole machine must be developed;
- **V6**: when \( 62.5 < v \leq 75 \), the whole machine structure has a certain fault, the fault parts must be repaired;
- **V7**: when \( 75 < v \leq 87.5 \), the whole machine is in good structural condition, just strengthen the patrol inspection;
- **V8**: when \( 87.5 < v \leq 100 \), the overall structure is in good condition.

### 4. Case study

Taking the metal structure of a port quay side container crane as the research object, the safety evaluation index system is established. The weight of each index is determined by the "0-4" score method, and the safety evaluation is carried out by the Fuzzy Comprehensive Evaluation (FCE). According to the characteristics of metal structure of quayside container crane, the safety evaluation index system of metal structure of quayside container crane is determined. The subsystem layer includes front girder, rear girder, cross beam, trapezoidal frame, column and tie rod. The single factor layer includes strength, rigidity, crack, corrosion, deformation and maintenance.

#### 4.1 Determination of Evaluation Value of Indicators

According to GB/T 5905-2011 "Standards and Procedures for Crane Test" and GB 6067.1-2010 "Safety Regulations for Lifting Machinery Part 1: General Provisions", data collection is carried out for a certain shore bridge to obtain the state value D. Through field testing and calculation, the evaluation value \( S \) of the single factor index of the quayside container crane is obtained, as shown in Table1.

| Structure          | Strength (MPa) | Rigidity (mm) | Crack (Z/day) | Corrosion (%) | Deformation (mm) | Maintenance (Z/day) | S     |
|--------------------|----------------|---------------|---------------|---------------|------------------|---------------------|-------|
| front girder       | 124            | 79.6          | 0.78          | 199           | 0.95             | 6.5                 | 0.35  | 0.76 | 150 | 0.92 |
| rear girder        | 108            | 9.8           | 0.97          | 138           | 0.93             | 3.4                 | 0.66  | 0.34 | 150 | 0.92 |
| cross beam         | 95             | 7.8           | 0.96          | 1000          | 0.99             | 2                   | 0.8   | 2.5  | 0.36 | 150 | 0.92 |
4.2 04-FCE Evaluation
Taking the calculation of the weight value of single factor index strength, rigidity, crack, corrosion, deformation and maintenance for the front beam as an example, experts or relevant technical personnel can calculate the weight value of each index by using the "0-4" scoring method after comparing the two indexes according to the importance of the index.

Weight of each index of front girder: $W_1 = (0.275, 0.176, 0.275, 0.098, 0.098, 0.098)$

By using the "distance normalization" method, the fuzzy relation matrix of the front beam subsystem can be obtained as follows:

$$R = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0.22 & 0.78 \\
0 & 0 & 0 & 0 & 0.26 & 0.74 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0.7 & 0.3 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.42 & 0.58 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.14 & 0.86 \\
\end{bmatrix}$$

The fuzzy evaluation set of the front girder is as follows:

$$B = (0, 0, 0.128, 0.055, 0, 0.066, 0.199, 0.551)$$

The evaluation result of the front beam $V_1$ is 78.83.

The other subsystems are similar to the above calculation process. We can get the following subsystems: rear beam subsystem $V_2 = 81.10$; cross beam subsystem $V_3 = 84.06$; trapezoidal frame subsystem $V_4 = 87.59$; column subsystem $V_5 = 69.49$; tie rod subsystem $V_6 = 91.88$, and the final evaluation value of the whole machine is 83.99.

4.3 Safety evaluation conclusion of the whole machine
After calculation, the safety evaluation value of the metal structure of the quayside container crane is 83.99, and the safety grade is 7. The safety state description of the whole structure corresponding to the evaluation result and the relevant treatment suggestions are as follows: the whole structure is in good condition, and the inspection can be strengthened. The practical application of 04-FCE evaluation method in a port for a period of time shows that it is reasonable and easy for port technicians to operate. It has certain universality and popularization value.

5. Summary
By analyzing the factors and characteristics affecting the safety of metal structure of quayside bridge, the safety evaluation index system of metal structure of quayside bridge is established, and the method of "0-4" score and fuzzy comprehensive evaluation (04-FCE) is put forward for the first time, which solves the common weight calculation results caused by the different professional and technical levels of scorers. There are large deviations, which are universal and easy to operate. Through case analysis and application, the safety of the metal structure of the whole quayside container crane is evaluated by 04-FCE. The evaluation results are basically consistent with the engineering practice. Therefore, this method can be used as the basis of the safety evaluation of the quayside container crane in the port, and provide support for improving the level of the safety management of the port machinery.

Acknowledgments
This article is supported by “The National Key Research and Development Program of China”, the project number is 2017YFC0805703, the research results of this paper come from the project.
References

[1] RMTR Ismail, ND That, QP Ha. Modelling and robust trajectory following for offshore container crane systems[J]. Automation in Construction, 2015(59):179-187.

[2] Ding Gaoyao, Li Aihua, Cao Xiongying, Zhao Zhangyan. Research Summary of Safety Assessment Methods on Container Crane[J]. Test Evaluation. 2017, 33(6):33-37.

[3] Shen G, Xiang D, Liu N, et al. Application of the Fuzzy-AHP Method in Bridge Crane Safety Evaluation[J]. Applied Mechanics and Materials, 2014, 496-500:2788-2794.

[4] Jian Zhang, Taizhou Li, Junwei Yao, Xiaowei Zhao. Safety Evaluation of General Gantry Crane Metal Structure Based on BP Neural Network [J]. Huadian Technology, 2014(3):24-28.

[5] CHEN Zhaofang, ZHANG Qishan. The safety evaluation for gantry system of portal crane based on the grey theory and analytic hierarchy process [J]. Journal of Fuzhou University (Natural Science Edition), 2013, 41(3):354-358.

[6] Li Aihua, Zhao Zhangyan. Crane safety evaluation based on fisher test [J]. Lifting and transporting machinery, 2015, (12):14-17.

[7] Li Aihua, Zhao Zhangyan. Crane safety assessment based on gametheory and uncertainty measurement theory [J]. Journal of Dalian Maritime University, 2016, (3):77-83.

[8] Zhishan Duan, Shanqiang Cui. Application of fuzzy analytic hierarchy process in mechanical safety evaluation [J]. Mechanical industry standardization and quality, 2007, (10):38-39.

[9] Li Yan. Research on Safety Evaluation System for Quayside Crane Based on Expert System [D]. Wuhan: Wuhan university of technology, 2015.

[10] Tong Maoxiang, Xu Hui, Wei Ning. Understanding and application of the new edition of lifting machinery safety regulations part 1: general provisions. Construction machinery (first half month).2012(6):73-75+80.