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Construction Safety Risk Assessment and Cause Analysis for High-Cable Tower Cranes †

Zhensong Ni [1], Shuri Cai [2,*] and Cairong Ni [2]

1 School of Big Data and Artificial Intelligence, Fujian Polytechnic Normal University, Fuzhou 350300, China; nizhensong@sina.com
2 Institute of Highway Science, Ministry of Transport, Beijing 100005, China; cairongni@gmail.com
* Correspondence: caishuri@126.com
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Abstract: In the construction of modern bridges, tower cranes are used for vertical transportation and hoisting. In erecting and removing tower cranes, a high degree of risk occurs. Thus, we evaluated the risk of using tower cranes in construction and proposed preventive measures.

Keywords: high-cable tower; tower crane; risk events; truss

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1. Introduction

Risks exist in life with the uncertainty of their occurrence. Haynes defined risk as an economic factor. Until the 1950s, risk management was not an independent discipline. Yet, the main research focuses on risks related to hazardous events and their probability of occurring. In this study, we proposed monitoring and early warning technology for preventing risks in bridge construction. The major risks in bridge construction are caused by the structural form of the bridge. The risk of occurrence is affected by various factors, such as changes in load and material, the inaccuracy of the calculation model, and human errors. Through risk assessment, a loss of investment, accidents, and social impacts can be reduced [1]. High-cable tower cranes are often used in construction, so the risk assessment of the cranes is important. Therefore, we analyzed the cause of risky events of the tower cranes to prevent accidents and propose preventive measures [2].

2. Risk of High-Cable Tower Crane

The safety risks of the high-cable tower crane include the toppling of the tower crane, the impact of buildings, falling off of heavy objects, broken arms of the tower crane, and falling of laborers. For those risks, the potential of the risk needs to be evaluated [3]. The risk assessment method of bridge construction and the mathematical model for uncertainty have been proposed using probability theory and statistics. We used random variables to indicate the times of the risk event and to evaluate the total amount of loss caused by risk events as follows:

$$L_{i.j} = \sum_{k=1}^{N_i} L_{i,j,k} \tag{1}$$

Referring to the previous research on the risk assessment of the construction safety of high-cable tower cranes, we classified the losses into three types: personnel fall, time delay, and monetary loss. A personnel fall refers to accidents in which workers fall on the site [4]. Time delay refers to a reduction in construction time due to the occurrence of risk events, and monetary loss is the value of material loss due to accidents. We weighted the three types of loss differently to obtain the combined effect of loss as follows:

$$L = L_h \times w_h + L_t \times w_t + L_m \times w_m \tag{2}$$

where w_h is the casualty weight, 0.45 according to the reference, w_t is the time delay weight, 0.25, and w_m is the currency loss weight, 0.3.

3. Probability Model of Risk Event

The probability model of the risk of the high-cable tower crane was defined as the probability and statistics related to the occurrence of the loss [5]. The state of personnel loss is expressed by the state equation z = r − s < 0, where *s* is the generalized effect under the action of a risk event *H*, and *r* is the generalized resistance. Then, the probability of loss is expressed as follows [6]:

$$P = p(R \le S) = \int_R^{\infty} f(S)\mathrm{dS} \tag{3}$$

The generalized effect *S* is related to the risk event *H*, so the probability density function for (*S*, *H*) is

$$f(S,H) = f(S|H)f(H) \tag{4}$$

where $f(S \mid H)$ is the conditional probability density function for the failure of the limit state in a given risk *H*, and $f(H)$ is the probability density function for the risk state *H*. The law of total probability is expressed with the following equations:

$$P = p(R \le S) = \int_R^{\infty}\left[\int_{-\infty}^{+\infty} f(S|H)f(H)\mathrm{dH}\right]\mathrm{dS} \tag{5}$$

$$\begin{aligned} P = p(R \le S) &= \int_R^{\infty}\left[\int_{-\infty}^{+\infty} f(S|H)f(H)\mathrm{dH}\right]\mathrm{dS} \\ &= \int_0^{\infty}\left[\int_R^{\infty} f(S|H)\mathrm{dS}\right]f(H)\mathrm{dH} \end{aligned} \tag{6}$$

$$F_s(H) = \int_R^{+\infty} f(S|H)\mathrm{dS}$$

where

$$P = \int_0^{+\infty} F_s(H)f(H)\mathrm{dH}$$

Considering the upper and lower limits H_1 and H_2 of the level at which a risk event *H* causes a loss, the above formula is transformed into the following:

$$P = \int_{H_1}^{H_2} F_s(H)f(H)\mathrm{dH} \tag{7}$$

where $F_s\left(\overline{H}_i\right)$ is the limit state failure probability for the H_i level of risk events in *i* interval, $\Delta F_0\left(\overline{H}_i\right)$ is the interval probability for the *i* level of risk events, and *N* is the number of the interval for the divided risk event level.

4. As Low as Reasonably Possible (ALARP) Principle

We used the ALARP criterion to determine the safety risk criterion in the construction of the high-cable tower crane [7]. First, we defined param to measure the construction risk and the basic characteristics of its mathematical functions according to param according to special values of the function to determine the level of and response to risk. The representative value of the function for decision-making was obtained through the questionnaire survey with the divided level of the risk grade as shown in Table 1.

Table 1. Level of risk classification of decision-makers.

Level of Risk	Negligible	Acceptable (ALARP)
Division level	$0 \leq R \leq 3$	$3 \leq R \leq 5$
Reasonable Control (ALARP)	**Strictly Controlled (ALARP)**	**Unacceptable**
$5 \leq R \leq 6$	$6 \leq R \leq 7$	$7 \leq R \leq 10$

The determined risk level from the risk level interval division table is presented in Figure 1. The division of risk level intervals was determined by the attitude of the risk decision-maker, and the attitude depended on the risk effect function. The risk level interval determines the names of each division area according to the ALARP risk decision-making criteria. The entire risk area was divided into unacceptable risk areas, negligible risk areas, and ALARP areas. Risk situations that fall into unacceptable areas must be reduced using mandatory measures. The risk situation in the negligible area can be ignored as the risk probability is far lower than the construction safety threshold.

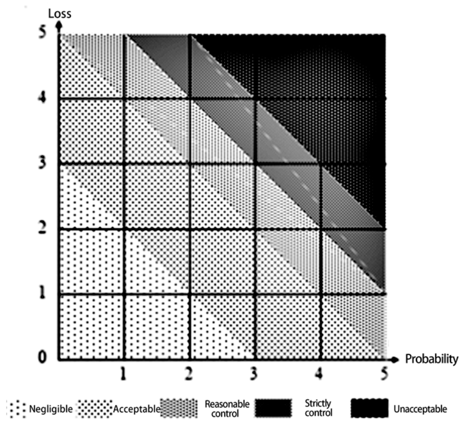

Figure 1. Risk level of decision-making.

The ALARP criteria are used for continuous functions and discrete functions. The risk matrix presents the embodiment of ALARP criteria in the form of a discrete function. The ALARP area, based on the different loss assessments of risk events, is divided into acceptable risk areas, reasonable risk control areas, and strict risk control areas.

5. Risk Event of High-Cable Tower Crane

- Tower crane overturning (GSTTD01):
  Due to the failure to meet the requirements for bearing capacity and ground flatness, it is easy for the tower body to tilt and the tower crane to overturn. During tower lifting and dismantling, tower overturning accidents may occur due to weak anchoring, insufficient strength or connection of steel wire ropes, control system failure, and improper use of traction capacity.
- Impact on tower body or other buildings (GSTTD02):
  Due to errors in cooperation between signal workers and operators, accidents sometimes occur when heavy objects collide with tower bodies or other buildings during the lifting process.
- Heavy objects falling off or tower crane arm breakage (GSTTD03):
  In the use of the tower crane, due to illegal lifting (the weight of the lifting object is not separated from the steel hook of the object below, the weight of the lifting object is unknown, and the operation action of the tower crane is suddenly changed), forced lifting, the hook falling off, the weight falling, or the tower crane limiter malfunctioning. These cause accidents of the tower crane overturning or arm breakage [8].

- Personnel fall (GSTTD04):
  In the process of lifting the tower crane, due to illegal operations, hidden dangers are not promptly eliminated, resulting in electric shock and personnel falling.

For the above four risk events, the losses of the Maanshan Tower crane with a high-cable tower were assessed. The assessment results are shown in Table 2. The loss assessment was calculated using Equation (2). The proportion of each weight is shown in Figure 2. The abscissa of Figure 2 shows the size of the loss assessment [9].

Table 2. Linear ratio of voltage to current.

Risk Event	Probability Level of Occurrence	Personnel Casualties	Time Delays	Currency Losses	Combined Effect	Loss Assessment
Tower crane overturning (GSTTD01)	2	3	1	2	2.4	4.4
Impact on tower body or other buildings (GSTTD02)	2	2	1	2	1.95	3.95
Heavy objects falling off or tower crane arm breakage (GSTTD03)	3	2	2	2	2.3	5.3
Personnel falling (GSTTD04)	2	2	1	2	1.95	3.95

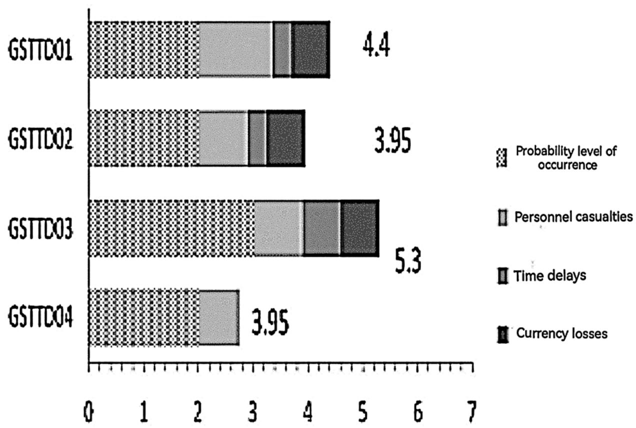

Figure 2. Proportion of each weight in risk assessment of steel tower column installation and loss assessment.

The loss assessment results of the risk situations during the construction of the high-cable tower crane were plotted in the risk level interval division table, as shown in Figure 2. The risk events GSTTD01, GSTTD02, GSTTD03, and GSTTD04 are located in the ALARP area. For the risks, reasonable safety precautions were required to reduce the occurrences. GSTTD01, GSTTD02, and GSTTD04 are located in the reasonable risk area and the acceptable risk area. General management measures were needed to reduce their construction risks without the need for further measures for the risks. For GSTTD03, prevention and caution were required to prevent the occurrence. In addition to general risk management, it was also necessary to consider the comparison result of the value of risk reduction and effect. Reasonable measures had to be taken for prevention and control to reduce its risks [10].

Possible risks need to be prevented and controlled. In Figure 3, in GSTTD03, heavy weight falling off or tower crane arm breaking are the risk events we focus on. Risk prevention and control measures must be formulated to reduce the risk of tower crane operation and avoid the occurrence of accidents [11].

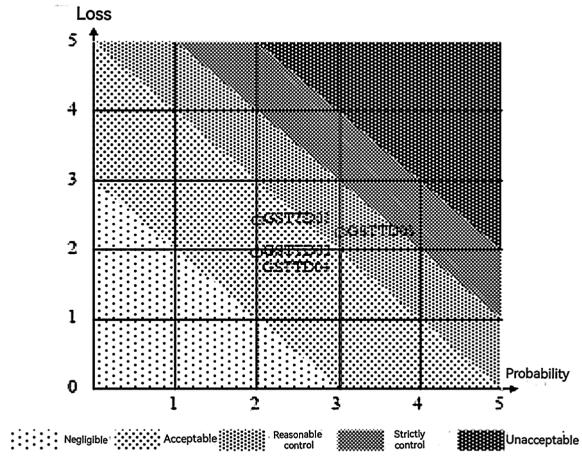

Figure 3. Risk event assessment.

6. Prevention and Control Technology

6.1. Tower Crane Safety Calculation

- Underframe: The upper part of the underframe is connected to the tower body, and the lower part is directly installed on a dedicated concrete foundation. It is composed of a base, a foundation section, and a diagonal brace [12].
- Tower body: The standard section of the tower body has two specifications according to its design strength, namely the lower tower body and the standard section. Each section is connected with 12-M39 special high-strength bolts, and the standard section of the same specification has interchangeability. The vertical members inside and outside the standard section are square cross-section members with a side length of 15 cm, while the horizontal members are square cross-section members with a side length of 10 cm. Each standard section has a length of 1.5 m, and every two standard sections are grouped. According to the construction requirements of the main tower, the tower crane used in this project has a height of 210 m.
- Lifting arm: The lifting arm is divided into 11 sections. There is a pull rod lifting point set on the upper chord of the third, seventh, and eighth sections of the arm. Each section of the arm is connected by a pin shaft, and a trolley traction mechanism is installed on the first section of the arm. The arm's end is equipped with a steel wire rope with an anti-torsion device. The maximum arm length is 70 m, and it can also be assembled into six types of arm lengths, including 65, 60, 52.5, 45, and 30 m. In this study, a 70 m boom was used for the analysis. The three main members on the outer side are square cross-section members with a side length of 15 cm. The remaining diagonal rods are steel pipes with an outer diameter of 7 cm and a wall thickness of 1 cm.
- Balancing arm: The balancing arm is divided into three sections, which are two sections of 7.5 m and one section of 4 m, connected by a pin. When the length of the lifting arm is 75, 65, or 60 m, the length of the balancing arm is 19 m. When the length of the lifting arm is 52.5 m, 45 m, or 30 m, the length of the balancing arm is 15 m. With the help of a pin, the balance arm and balance arm pull rod are connected to the rotating tower body and top as a whole, and there are railings and walkways on both sides of the balance arm. The two outer members of the balance arm are square cross-section members with a side length of 15 cm. The rest are steel pipes with an outer diameter of 10cm and a wall thickness of 1 cm.
- Upper and lower supports: The upper support is installed on top of the slewing bearing and connected to the inner ring of the slewing bearing. The lower support is a box-shaped support for the non-rotating part of the crane, which is equipped with an outer gear ring of the slewing support on its upper plane. The lower support is connected to the outer ring of the slewing support through bolts, and the relative rotational motion between the upper and lower supports is achieved through the use

of a slewing mechanism. The tower is connected to the upper support and turn-around, and the tower to the standard section below the lower support.

- Rotating tower body: The lower end of the rotating tower body is connected to the upper support with 16 high-strength bolts, the upper part is connected to the tower top pin, and the front and rear ear plates are connected to the balance arm and lifting arm, respectively. The upper part is equipped with a lifting weight limiter.
- Tower top: The tower top is an inclined cone, with the upper end connected to the lifting arm and balance arm through a pull rod to keep the two arms horizontal. The lower end is connected to the rotating tower body with four pins. To install the lifting arm pull rod and balance arm pull rod, a working platform and pulley block are installed on the upper part of the tower top.

6.2. Parameter Description: Q235 Type Steel

According to the "Code for Design of Steel Structures" (GB50017-2003), design tensile and compressive and flexural strength are f = 215 N/mm^2. Design shear strength is fv = 125 N/mm^2. The elastic modulus is E = 2.05 $\times$ 10^3 N/mm^2.

6.3. Model Establishment

The model-simplified tower crane consisted of a main support truss and a boom truss. The boom was connected by four cables to bear the load of counterweights and goods. The base was fixed [7]. A 3D beam element beam44 was used for the model of the truss of the tower crane. LINK10 was used to model the cable in Figure 4. Because the structural layout of the tower crane has repetitive characteristics, the basic structural cell of the truss is constructed and then copied. The counterweight of the tower crane and the lifted goods were treated as load equivalents. After constructing the tower crane structure, the strength analysis of the components in the structure and the layout analysis of the cable positions were carried out.

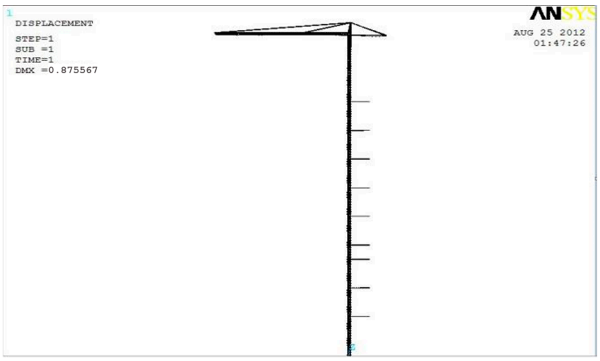

Figure 4. Truss of tower crane.

The only deformation of the tower crane without a load added at the boom end is shown in Figure 5. One end of the lifting arm was slightly raised by 0.8 m, and the entire arm end remained horizontal. Under normal use, the displacement and deformation of the structure met the requirements. When the lifting arm was 70 m away and the ultimate load was 3.4 tons, the entire structure moved down along one side of the lifting arm at a distance of 2 m. However, due to the long lifting arm, the entire structure remained approximately horizontal.

For a 3.4-ton weight applied at the end of the lifting arm, the internal force distribution of the entire tower crane is shown in Figure 6.

The maximum values of tension and pressure borne by the members were observed at the diagonal cables and lifting goods. In addition, the stress at the connection between the lifting arm and the tower body made the entire tower crane structure weak. According to the calculation results, the maximum stress borne by the cable was 907,180 Pa. Therefore, the stress met the strength requirement of less than 215 MPa.

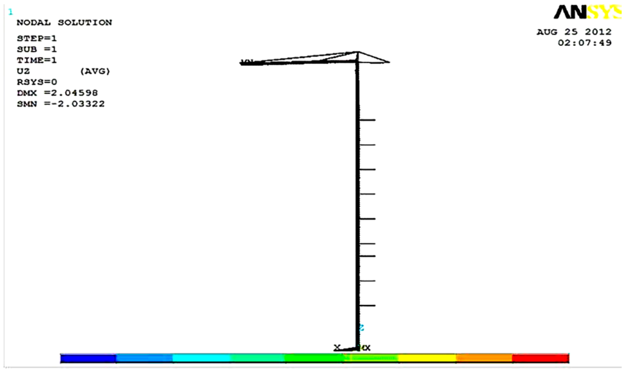

Figure 5. Truss of tower crane with load.

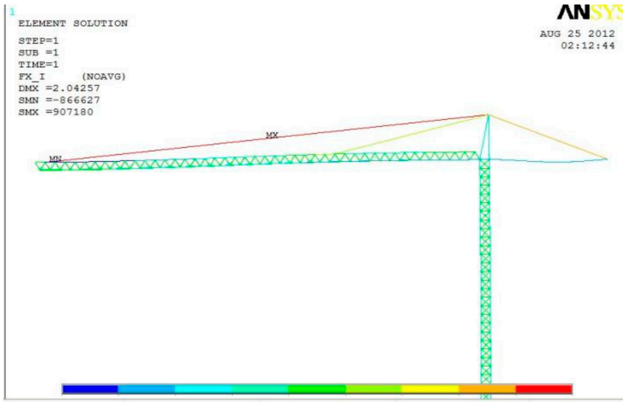

Figure 6. Internal force distribution diagram of tower crane truss.

Figures 7 and 8 show tower crane safety monitoring.

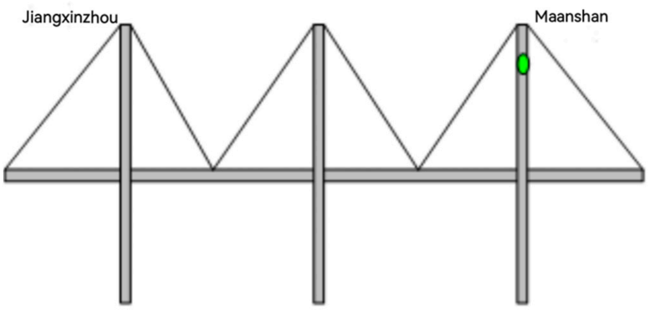

Figure 7. Overall schematic diagram of tower crane safety monitoring.

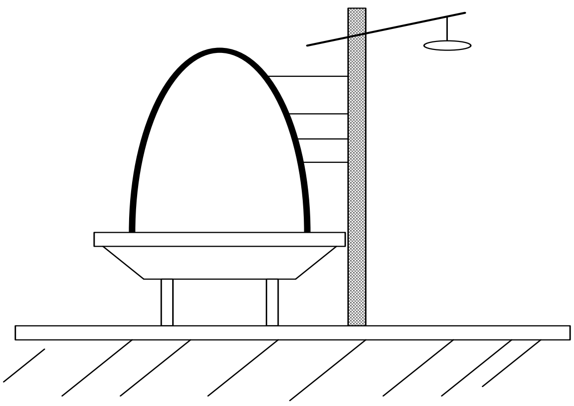

Figure 8. Cross-section diagram of tower crane safety monitoring.

A wireless cable force sensor was installed at the position of the diagonal cable to measure the changes in cable force and install an alarm on-site. Once the cable force sensor detected that the cable force value exceeded the calculated value, an alarm was issued immediately to stop the tower crane work and check the condition of the tower crane. In addition, the stress at the connection between the boom and the tower body made the entire tower crane structure weak. The stress change at the connection between the boom and the tower body was measured using wireless dynamic strain sensors, and an alarm was issued when the threshold was exceeded.

7. Conclusions

In bridge construction, bridge piers and cable towers are installed at a high altitude with small working spaces. The selection and layout of tower cranes are the keys to construction, as the time for the total construction of the entire bridge is affected by the performance of the cranes. The selection and layout of tower cranes are conducted with a comprehensive analysis process, and the relevant parameters of tower cranes must be determined based on the actual situation and construction requirements of each bridge's structural form, scale, and terrain conditions at the bridge location. On this basis, the tower crane must be reasonably matched and arranged according to its performance indicators. Based on the different sources of risk, the structure and construction characteristics of tower cranes can be analyzed. We determined safety prevention and control technology for tower crane construction and proposed corresponding preventive measures for risk events. A 3D beam element beam44 was used to model the truss of the tower crane, and LINK10 was used to model the cable. The maximum stress borne by the cable was calculated to be less than the threshold value. Using the proposed model of the truss of the crane, the changes in cable force and installed alarms on-site were measured. Once the cable force sensor detected the cable force exceeding the calculated value, an alarm was issued immediately to stop the tower crane operation and check its condition to avoid accidents.

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