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Research Article

Probability Analysis of Crane Load and Load Combination Actions

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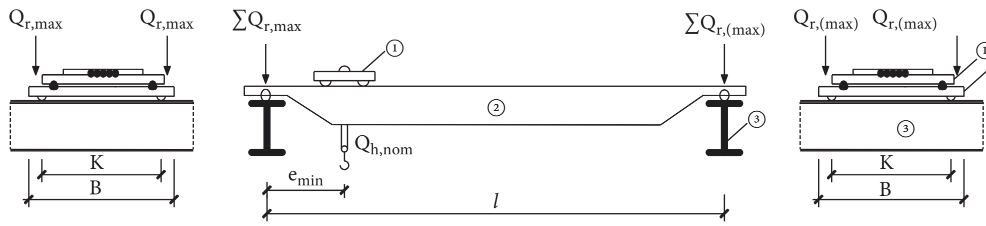
This study presents probability models of crane load and load combination actions for reliability analysis of the industry buildings. Crane load values are simplified here only varying in time, and load combination actions only vary in space. With the feasible survey program and K-S test, the Gumbel distribution is chosen as the probability distribution of the arbitrary point-in-time crane load values with the statistical investigation data. With the simple stationary binomial random process model hypothesis and the block maxima method, it determined that the maximum value of crane load during the design reference period also follows the Gumbel distribution, with the peaks-over-threshold method evaluation. For multiple crane load combination actions, the modified Turkstra rule is improved to determine the probability distribution of the actions as the Gumbel distribution by considering the occurrence probability, numbers, location, and values of each crane load acting on the influence line, evaluated by the Monte Carlo simulations. Design standard values for crane loads and load combination actions, as specified in building codes, are evaluated based on these distributions in probability significance. The calculation results illustrate that the design standard values for crane loads are relatively safe and conservative.

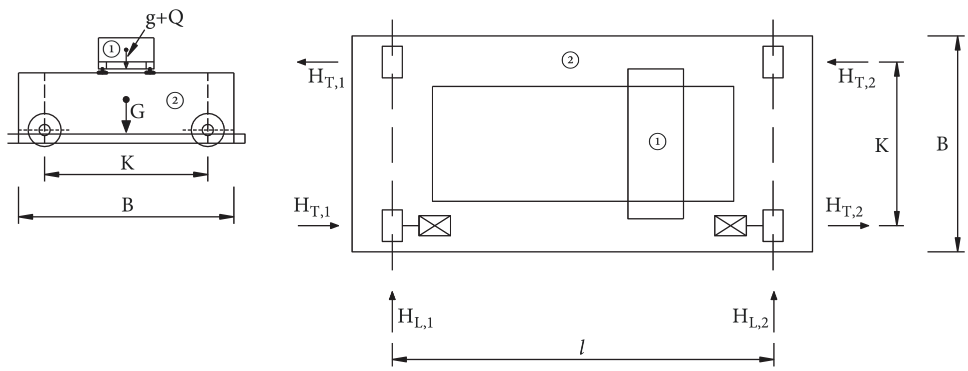
1. Introduction

Crane load is a free dynamic action, which has arbitrary spatial distributions over crane supporting structures within given limits and causes significant structural acceleration. Crane load is a random variable varying in time and space dimensions within the design reference period and is denoted as random field model [1, 2]. General specifications stipulate the design value of the crane load and load capabilities, such as EN1991-3: Eurocode 1-actions on structures-Part 3: actions induced by cranes and machinery [1], ACSE/SEI 7-05: minimum design loads for buildings and other structures [3], and GB50009-2012: load code for the design of building structures [4]. However, these codes do not give an acceptable load probability models except GB50009-2012 [4] which have done some traditional statistical surveys and load experiments while lacking theoretical analysis to give instructions on the validity of these data. That is to say, for the dynamic action in these codes, there are no acceptable load probability models for crane load and load actions have been approved for reliability analysis. It means the actual reliability of the industry buildings designed with these above codes of considering the crane loads is unknown.

In the Probabilistic model code of the Joint Committee on Structural Safety (JCSS) [5], it proved the basis method on building the probability models for load and load actions. That is, determining the probability distribution of the arbitrary point-in-time values with the statistical investigation data in independent statistical interval, and the probability distribution of the maximum values during the design reference period by being simplified to the stationary binomial random process. When more than one variable loads act in combination, simplified rules such as JCSS or Turkstra combination rule applied to the reliability calculation of the first-order second-moment method (FOSM) are applied to the load action probability model. But crane load is much different with other live loads when using the model code. In industry building, crane load and their combination actions are functions of both time and space [6]. The time variable shows the different crane load values in different points in time. The space variable includes the position of the crane and the crab (Figure 1). To determine the probability



(a) Load arrangement of the loaded crane use to obtain the maximum vertical load on the runway beam



(b) Load arrangement of longitudinal and transverse horizontal wheel forces caused by acceleration and deceleration

FIGURE 1: Schematic diagram of load arrangements of the vertical load and horizontal force, where ① is the crab; ② is the crane bridge; ③ is the crane beam. $Q_{r,max}$ is the maximum load per wheel of the loaded crane. $Q_{r,(max)}$ is the accompanying load per wheel of the loaded crane. $\sum Q_{r,max}$ is the sum of the maximum loads $Q_{r,max}$ per runway of the loaded crane. $\sum Q_{r,(max)}$ is the sum of the accompanying maximum loads $Q_{r,(max)}$ per runway of the loaded crane. $Q_{h,nom}$ is the nominal hoist load. e_{min} is the minimum distance between the hoist point and the crane wheel. l is the span of the crane bridge. K is the wheel distance of the crane. B is the width of the crane. g is the self-weight of the crab. G is the self-weight of the crane. Q is the hoist load. $H_{T,i}$ $(i = 1, 2)$ is the transverse horizontal wheel forces. $H_{L,i}$ $(i = 1, 2)$ is the longitudinal horizontal wheel forces.

distribution of the point-in-time crane load values, the worst-case situation should be considered in the simplified analysis, considering the actual measured maximum load for the crab worst-case position (in Figure 1), but the independent statistical interval is too long to do the investigation and obtain enough samples (with the operating period as 20 years). And to determine the probability distribution of the crane load actions with multiple cranes acting on a beam, the traditional JCSS or Turkstra combination rule considering the different load actions is not effective, for multiple cranes with respective crane loads acting different with multiple loads. It is much more dependent on the actual production process, and with little uncertainty with survey results. With actual investigation, if multiple cranes are acting on beam, the synchronous occurrence probability of two cranes on the span beam is 1 (it means in the operating period, two cranes will simultaneously act on the same span beam more than once) and the synchronous occurrence probability of three cranes is almost 0. That is to say, two cranes are certainly synchronous at least once. If two cranes are synchronous, the possible computational maximum load (with 'full load' for each crane) is almost zero. When determining the probability model and statistical parameters for crane load combination actions, these above two points need to be considered.

In this paper, the available method was improved to obtain the enough samples and certificate the availability of the investigation data of [4], to obtain the probability distribution of the arbitrary point-in-time crane load values with the time-space exchange method theory and the time-space-dimensional variable separation method. And it modified the Turkstra rule to determine the probability model of the multiple crane load combination actions based on the actual operating case. The probability model of crane load and load combination actions can be improved as follows. Firstly, simplifying a crane load action process as the stationary binomial random process, the design reference period is divided into equal independent intervals, using the time-space exchange method theory and the time-space-dimensional variable separation method to determine the executable observation interval. With the actual survey data, the probability distribution of the arbitrary point-in-time crane load values is determined, considering only time and crab position variability. Secondly, the probability distribution of the random maximum process load during the design reference period is derived with the stationary binomial random process theory and the block maxima method [7]. Lastly, the crane position variable is considered with the occurrence probability along the crane beam influence line during the operation period [4]; the modified Turkstra rule is improved to calculate the multiple crane load combination actions considering the occurrence probability, occurrence load values, and occurrence position. The influence line is ensured by the worst-case effect of the load actions (Figure 1(a)). What is more, the above simple methods obtained the distribution expression formulas of the crane loads and multiple crane load combination actions can be directly used for FOSM reliability calculation. With the peaks-over-threshold method (more precise but could not prove expression formula) to verify the distribution of the crane loads and the Monte Carlo simulations (more precise but could not prove expression formula) to verify the distribution of the multiple crane load combination actions; these above simple methods and distribution functions are acceptable.

The rest of this paper is arranged as follows. Section 2 states the arbitrary point-in-time distribution and the maximum value distribution during the crane load design reference period and improves the distribution of multiple crane load combination actions using the influence line method. Section 3 constructs the evaluated results of the above distribution with the peaks-over-threshold method for crane loads and Monte Carlo simulations for multiple crane load combination actions. The probability evaluated significance of the design standard crane load and load combination methods specified in Chinese load code are introduced in Section 4. Finally, Section 5 presents the conclusions.

2. Probability Models of Crane Load and Load Combination Actions

2.1. Methods of Building Crane Load Model. Multiple estimation methods for building load models during the design reference period have been developed, including the block maxima method [8, 9] and peaks-over-threshold (POT) method [8, 10]. The block maxima method is based on the stationary binomial random process model hypothesis and the extreme value distribution theory of random variables. It divides the complete time history sample into equally sized blocks and extracts the maximum load values from each block. Assuming that the block maximum is independently and identically distributed, the distribution of extremes is then determined. In order to ensure model accuracy, the load, as a broad stationary stochastic process, should be independent during the block maximum [9, 11, 12]. This block maxima method can prove an expression formula of the maximum value distribution during the crane load design reference period for FOSM reliability calculated. The POT method deals with multiple independent peaks above a preselected high threshold, and the extreme value theory warrants use of a generalized Pareto distribution (GPD) as an adequate model for peaks over the threshold [10, 13, 14]. The POT method contains a more precise theory than the block maxima method, but with much more complex calculations and without expression formula [15, 16]. In this paper, the block maxima method was used to build the crane load model with an expression formula, and the POT method was used to evaluate the model result.

Crane load is only determined using the hoist weight and the crab position from the survey results. To simplify, the crane load value only considers time randomness and is seldom of immediate relevance to the crane position. And crane load actions are affected by crane position, with the location of each crane having only space randomness. That is to say, the macroscopic statistical law for the crane action (the number and location on the influence line) has nothing to do with time, but the position of adjacent cranes with respect to each other is restricted. Considering the above features of crane load through time, it can be simplified to a stationary binomial random process to improve probability distributions of the arbitrary point-in-time values and maximum values during the design reference period. And considering the space randomness features of crane load action, crane load combination actions can be calculated using the combination method on the influence line [4].

This study only discusses the overhead traveling crane and crane beams to illustrate this method. With different characteristics and load conditions for different crane classifications, eight working levels of overhead traveling cranes are used in China. Within the same working level, cranes have different weight classes, hoisting heights, and working speeds. To ensure a proper probability analysis for crane load and actions, different working levels should be distinguished. Crane load includes a vertical load and horizontal force with different load directions. The vertical load is composed of the weight of the hoisted block and the hoist load, generally shown as vertical wheel loads on a runway beam [4]. The maximum vertical load is determined by considering the load arrangements shown in Figure 1(a). Horizontal forces include the longitudinal horizontal force and transverse horizontal force. The longitudinal horizontal force acts horizontally at the traction surface of the runway beam in either direction parallel to the beam. The transverse horizontal force acts horizontally at the traction surface of the runway beam in either direction, perpendicular to the beam, and is equally distributed on each side of the crane bridge (Figure 1(b)). Here we only consider the transverse horizontal force.

2.2. Crane Load Arbitrary Point-In-Time Distribution. When considering a single crane load on the influence line, the following assumptions of a stationary binomial random process for the crane load (vertical loads and horizontal forces) are necessary:

(1) The design reference period T is divided into r equal statistical intervals τ ($r = T/\tau$), and the maximum crane load in each interval is independent.

(2) In each statistical interval, the occurrence probability for the maximum crane load is 1, while the nonoccurrence probability is 0.

(3) The probability distribution for the maximum crane load $Q_{\max}(\tau)$ in interval τ can be denoted with

$$F_{Q_\tau}(x) = P\left[Q_{\max}(\tau) \le x\right] \tag{1}$$

where the function $F_{Q_\tau}(x)$ can be called the arbitrary point-in-time value probability distribution, which is determined by the magnitudes of the maximum crane load in different intervals.

For a general crane beam in China, the design reference period is commonly 50 years [4]. The longer the design life, the higher the probability that the maximum load occurs. This is related to the design reference period and is affected by the frequency of crane replacement, the operating cycle, vacancy time, nominal hoist load, and crane working level. Generally, crane vacancy is not considered during the design life. The replacement frequency and operating cycle are determined according to survey results. To ensure independence of the maximum crane load in each interval τ, the operating period should be regarded as the statistical interval of crane replacement. The operating period, including the nonoperating and operating period of time, depended on the crane replacement time. According to the design code for cranes: the GB/T 3811-2008 [17], the ГОСТ 27584-88 [18], and the ГОСТ 22827-85 [19], the operating period for an overhead traveling crane is 20 years. Thus, the equal statistical interval τ should be taken as 20 years.

Normally, during each operating period, the nominal hoist load and work level of the crane and other main technical parameters do not change after replacement [4]. Crane load values and maximum crane load values are random and need to be considered for structural reliability analysis. To simplify, the maximum crane load value in each statistical interval is assumed to follow the same probability distribution [12]. Meaning the maximum crane load $Q_{\max}(\tau)$ in each interval is a nonnegative random variable, and the probability distribution during different intervals is identical. Load through, in theory, should be obtained with the maximum crane load values in each statistical interval by statistical investigation, but the statistical interval τ is too long to obtain enough samples. A feasible method for effective investigation should be put forward.

As a tool of moving and transporting material, cranes are used in various fields to handle heavy objects [6]. Generally, when the crane structure is engaged in regular heavy work, there is a small observation interval $\Delta\tau$ in which all possible crane operating conditions within a complete operating period can be observed. The observation interval $\Delta\tau$ should be determined according to the nominal hoist load, work level, and production cycle to ensure that crane loads in this small observation interval provide the sufficient record with a complete load history. Additionally, the chosen $\Delta\tau$ should ensure that crane loads in every observation interval are identical and completely relevant. The values of $\Delta\tau$ are empirically estimated from observations and consultations with operators and factory employees. The maximum crane load in the observation interval is determined by statistical surveys and load experiments.

According to the time-space exchange method theory, the maximum crane load samples during the statistical intervals τ (actually measured in observation interval) for many similar crane types (but not the same crane) in their respective working plants with spatial-dimension statistics, can be approximated using samples from several statistical intervals of the same crane through time. The distribution can be determined from these samples and validated using the K-S test. Reference [4] did the actual survey on 57 cranes with the light, medium, and heavy working level in different factories with different production process in Beijing, Shanghai, Shenyang, Anshan, Dalian, and so on. It choose the maximum crane load in about 5 years (means the observation interval $\Delta\tau$ here is taken as 5) as the statistical data. Using the above-mentioned method, the statistical results from [4] can be used to improve the probability distribution of the arbitrary point-in-time crane load values.

For the vertical load and transverse horizontal force of overhead traveling cranes, the probability distribution of the arbitrary point-in-time crane load values are expressed as $F_{\mathrm{VS}}(x)$ and $F_{\mathrm{HS}}(x)$. These two loads, respectively, refer to the maximum wheel pressure and the maximum transverse horizontal force caused by acceleration or deceleration of the crab in relation to its movement along the crane bridge. Actually, the transverse horizontal force here includes the force caused by the skewing of the crane in relation to its movement along the runway beams. At different working levels, nominal hoist loads result in large divergences, and the 'unified standard for reliability of building structures' uses dimensionless quantities to normalize the original data with actual measured values ($W_{\mathrm{C}_{\mathrm{measured}}}$ or $D_{\mathrm{HK}_{\mathrm{measured}}}$) for the corresponding standard design value ($\mathrm{W_C}$ or $\mathrm{D_{HK}}$) [20]. $\mathrm{W_C}$ is the nominal maximum wheel pressure; $\mathrm{D_{HK}}$ is the sum of the nominal hoist load $\mathrm{Q_{HK}}$; and g is the self-weight of the crab [17]. Statistical results for different working level cranes are discussed below. According to survey results in [4] and K-S test, the Cumulative Distribution Functions (CDFs) of the $F_{\mathrm{VS}}(x)$ and $F_{\mathrm{HS}}(x)$ are expressed as

$$F_{\mathrm{VS}}(x) = \exp\left\{-\exp\left[\frac{-\alpha_{\mathrm{VS}}(x-\beta_{\mathrm{VS}}W_{\mathrm{C}})}{W_{\mathrm{C}}}\right]\right\} \tag{2}$$

$$F_{\mathrm{HS}}(x) = \exp\left\{-\exp\left[\frac{-\alpha_{\mathrm{HS}}(x-\beta_{\mathrm{HS}}D_{\mathrm{HK}})}{D_{\mathrm{HK}}}\right]\right\} \tag{3}$$

where the subscripts VS and HS refer to the arbitrary point-in-time values of the vertical load and the transverse horizontal force; α_{VS}, α_{HS} and β_{VS}, β_{HS} are the scale and location parameters, respectively, calculated as $\alpha_{\mathrm{VS}} = 1.2825/\sigma_{\mathrm{VS}}$, $\beta_{\mathrm{VS}} = \mu_{\mathrm{VS}} - 0.5772/\alpha_{\mathrm{VS}}$, $\alpha_{\mathrm{HS}} = 1.2825/\sigma_{\mathrm{HS}}$, and $\beta_{\mathrm{HS}} = \mu_{\mathrm{HS}} - 0.5772/\alpha_{\mathrm{HS}}$, where μ_{VS}, μ_{HS}, and σ_{VS}, σ_{HS} are the total means and standard deviations approximated by the sample means and standard deviations. The values of these statistical results and model parameters for different working levels and nominal hoist loads are listed in Table 1 [4]. Considering the fact that transverse horizontal forces are primarily affected by the nominal hoist load, the statistics of the working level are not distinguished.

2.3. Maximum Crane Load Distribution during the Design Reference Period. Using the stationary binomial random process model described in Sections 2.1 and 2.2, the crane load sample function can be represented as a rectangle wave function with equal intervals [5]. The maximum value in random process $Q_{\max}(T)$ during the design reference period T should be the maximum statistical interval $Q_{\max}(\tau)$. $Q_{\max}(T)$ is a random variable of $Q_{\max}(T) = \max_{0\le t\le T}[Q_{\max}(\tau)]$, whose probability distribution is [5, 20]

$$\begin{aligned} F_{Q_T}(x) &= P\left\{Q_{\max}(T) \le x\right\} \\ &= P\left\{\max_{0\le\tau\le T}\left[Q_{\max}(\tau)\right] \le x\right\} \\ &= \prod_{j=1}^{r} P\left\{Q_{\max}(\tau) \le x, \tau \in \tau_j\right\} \approx \left[F_{Q_\tau}(x)\right]^{T/\tau} \end{aligned} \tag{4}$$

Table 1: Crane load probability model and statistical parameters.

	Working level	Q_{HK}/t	The arbitrary point-in-time value distribution statistical results [4]		The arbitrary point-in-time value distribution model parameters		The maximum value distribution ($T = 50a$) Moments		The maximum value distribution ($T = 50a$) model parameters	
			μ_{VS}	σ_{VS}	α_{VS}	β_{VS}	μ_{VM}	σ_{VM}	α_{VM}	β_{VM}
THE VERTICAL LOAD	Light A1-A3	2	0.520	0.055	23.318	0.495	0.559	0.055	23.318	0.535
		3	0.460	0.071	18.063	0.428	0.511	0.071	18.063	0.479
		5	0.370	0.069	18.587	0.339	0.419	0.069	18.587	0.388
	Medium A4-A5	5	0.610	0.037	34.662	0.593	0.636	0.037	34.662	0.620
		10	0.520	0.045	28.500	0.500	0.552	0.045	28.500	0.532
		15/3	0.490	0.050	25.650	0.467	0.526	0.050	25.650	0.503
		20/5	0.420	0.041	31.280	0.402	0.449	0.041	31.280	0.431
	Heavy A6-A7	5	0.640	0.071	18.063	0.608	0.691	0.071	18.063	0.659
		10	0.490	0.069	18.587	0.459	0.539	0.069	18.587	0.508
		15/3	0.500	0.056	22.902	0.475	0.540	0.056	22.902	0.515
		30/5	0.460	0.065	19.731	0.431	0.506	0.065	19.731	0.477
		50/10	0.380	0.050	25.650	0.357	0.416	0.050	25.650	0.393
THE HORIZONTAL FORCES		Q_{HK}/t	μ_{HS}	σ_{HS}	α_{HS}	β_{HS}	μ_{HM}	σ_{HM}	α_{HM}	β_{HM}
		5	0.079	0.028	45.804	0.066	0.099	0.028	45.804	0.086
		10	0.053	0.016	80.156	0.046	0.064	0.016	80.156	0.057
		20	0.046	0.014	91.607	0.040	0.056	0.014	91.607	0.050
		30	0.043	0.011	116.591	0.038	0.051	0.011	116.591	0.046
		75	0.038	0.013	98.654	0.032	0.047	0.013	98.654	0.041

Note. The actual statistical results for vertical load and transverse horizontal force should be multiplied by W_C and D_{HK}, respectively. The crane nominal hoist load is represented by Q_{HK}. The horizontal forces here refer to the total forces on the two sides of the crane bridge.

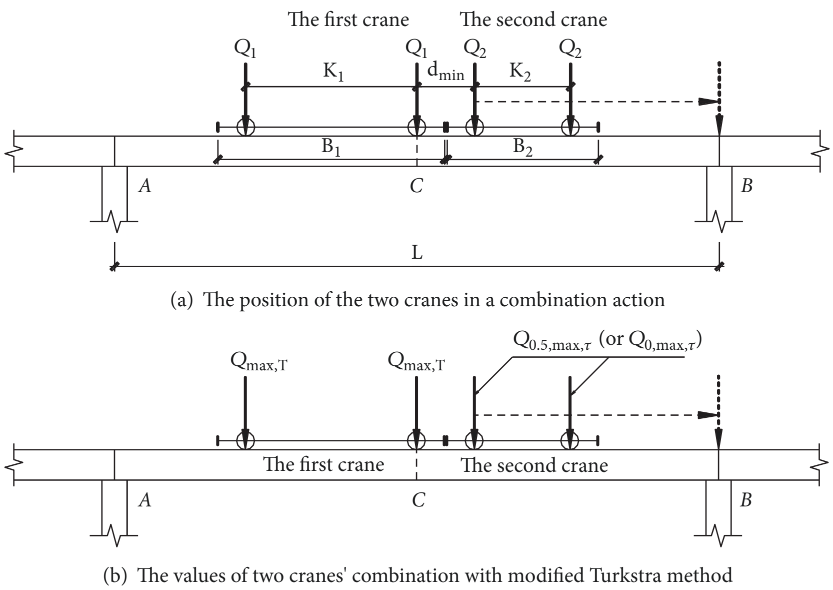


Figure 2: Schematic diagram of two cranes acting in combination on a runway beam. Note: L is the adjacent column spacing (the span of the crane beam); point A and point B are the crane beam bearing connections; point C is the mid-span position of the beam; B_i $(i = 1, 2)$ is the width of the crane; K_i $(i = 1, 2)$ is the wheel distance of the crane; and $Q_i(x)$ $(i = 1, 2)$ expresses the load (vertical load or horizontal force) for each crane.

The maximum value probability distribution of vertical load and horizontal force during the design reference period, obtained using (4) and the corresponding arbitrary point-in-time value distribution given by (2) and (3), is expressed as a Gumbel (type I) distribution of $F_{VM}(x)$ and $F_{HM}(x)$

$$\begin{aligned} F_{VM}(x) &= [F_{VS}(x)]^{T/\tau} \\ &= \exp\left\{-\exp\left[\frac{-\alpha_{VM}(x-\beta_{VM}W_C)}{W_C}\right]\right\} \end{aligned} \tag{5}$$

$$\begin{aligned} F_{HM}(x) &= [F_{HS}(x)]^{T/\tau} \\ &= \exp\left\{-\exp\left[\frac{-\alpha_{HM}(x-\beta_{HM}D_{HK})}{D_{HK}}\right]\right\} \end{aligned} \tag{6}$$

where the subscripts VM and HM represent the mean maximum value of vertical load and horizontal force, respectively, during the design reference period. α_{VM}, α_{HM} and β_{VM}, β_{HM} are the scale and location parameters, calculated as $\alpha_{VM} = \alpha_{VS} = 1.2825/\sigma_{VS}$, $\alpha_{HM} = \alpha_{HS} = 1.2825/\sigma_{HS}$, $\beta_{VM} = \beta_{VS} + \ln(T/\tau)/\alpha_{VS}$, and $\beta_{HM} = \beta_{HS} + \ln(T/\tau)/\alpha_{HS}$. Mean values and standard deviations μ_{VM}, μ_{HM} and σ_{VM}, σ_{HM} are calculated using $\mu_{VM} = \beta_{VM} + 0.5772/\alpha_{VM}$, $\mu_{HM} = \beta_{HM} + 0.5772/\alpha_{HM}$, $\sigma_{VM} = 1.2825/\alpha_{VM}$, and $\sigma_{HM} = 1.2825/\alpha_{HM}$. Parameters for different working levels and nominal hoist loads are listed in Table 1. The design reference period T and the statistical intervals τ are taken as 50 years and 20 years, respectively.

2.4. Probability Distribution of Multiple Crane Load Combination Actions. To determine the probability distribution of multiple crane load combination actions, the occurrence probability as well as the number and emergence location on the influence line must be confirmed. Then a combination probability model using influence line method can be determined. This paper uses the influence line of the crane beam mid-span bending moment (point C in Figure 2) as an example to illustrate the theoretical method. Other combination crane actions on the crane beam or column should be the same.

2.4.1. Number and Location of Cranes. Although we assume that the random number of cranes on the influence line has nothing to do with the time interval, the most possible case with the number of cranes on a crane beam should be obtained by observation over each observation interval. The number of cranes on a span crane beam is an uncertain variable; however, it is simplified as the certain number about the most frequent maximum number in the observation interval for reliability analysis [20]. Cranes that operate together should be treated as a single crane to determine the combination actions. If several cranes operate independently, meaning the combination action varies in time, the number of cranes to be considered in the worst-case position may be specified by an engineering survey. Considering the design load such as EN1991-3 [1], ASCE/SEI 7-05 [3], and GB50009-2012 [4], and the survey of [21] in China, two-crane combination on the same crane beam is considered. Additionally, if the maximum number in each observation interval is recommended as the sample for investigation, the two-crane load occurrence probability is approximately 1. This would be the worst-case statistical interval for analysis, having nothing to do with time. Therefore, two cranes should be considered when determining the distribution of the crane load combination actions on the bending moment influence line [21].

One crane is taken as always located at the worst-case position on the crane beam, and the second crane moves based on a uniform distribution along the adjacent operating range (Figure 2(a)).

2.4.2. The Modified Turkstra Method for Crane Load Combination Actions. When multiple cranes act on the influence line, it is almost impossible that each crane operated at their respective maximum load values. If these maximum values are used together, the combination result will be too conservative. Therefore, when determining the design combination coefficient of multiple crane loads, short-term crane loads should be taken into account [21]. The heavy working level (A6-A7) cranes are considered to be "one full and one-half"; medium and light working level (A1–A5) cranes are considered as "one full and one empty." Here the "full," "half," and "empty" terms refer to the crane hoist load being full, half, and zero compared to the nominal hoist load Q_{HK} [2, 4]. This suggestion comes from engineering research [21] and takes the impact of the crane working level into account.

To determine the distribution for multiple crane load combination actions, the Turkstra method is modified as follows. With two cranes acting on the beam, the main crane (commonly with the larger crane load) is taken as the first crane located at the worst-case position, and the adjacent crane is taken as the second crane, whose position is regarded as a uniform distribution along the operating range. The occurrence probability of each crane on the influence line is 1. The first crane takes the "full load," meaning the maximum load during the design reference period T. The second crane takes the "half load" or "empty load," respectively, for A6-A7 or A1–A5 working levels, meaning reduced arbitrary point-in-time values within the statistical interval τ. The modified Turkstra combination method shows the worst-case combination of the two cranes for the bending moment of the mid-span (point C), where $Q_{\max,T}$ is the maximum value of "full load" during the design reference period (the vertical load $V_{\max,T}$ and the horizontal force $H_{\max,T}$) (Figure 2(b)). $Q_{0.5,\max,\tau}$ and $Q_{0,\max,\tau}$ are the "half" and 'empty' loads of the reduction arbitrary point-in-time values (the vertical load $V_{0.5,\max,\tau}$, $V_{0,\max,\tau}$ and the horizontal force $H_{0.5,\max,\tau}$, $H_{0,\max,\tau}$).

2.4.3. Probability Models for Multiple Crane Combinations. When the first and second cranes are located at the worst-case position along the influence line, the sum of the influence line ordinates is expressed as $y_{1,\max} = (\mathrm{L}-\mathrm{K}_1)/2$ and $y_{2,\max} = (\mathrm{L}-\mathrm{K}_2)/2 - \mathrm{d}_{\min}$. Considering the probability combination, the actual values are expressed as y_1 and y_2. With the modified Turkstra method, $y_1 = y_{1,\max}$, and y_2 is taken as a random value in the random interval $[0, y_{2,\max}]$. When the second crane position follows a uniform distribution within its operating range, y_2 follows a piecewise uniform distribution, expressed as a function of distance d between the adjacent wheels of the two different cranes. Based on the analysis in Section 2.4.2, the first crane is fixed, and the second crane follows a uniform distribution of distance $\mathrm{U}[\mathrm{d}_{\min}, \mathrm{L}/2]$, where $\mathrm{d}_{\min} = (\mathrm{B}_1 + \mathrm{B}_2 - \mathrm{K}_1 - \mathrm{K}_2)/2$ is the minimum distance between the adjacent wheels of the two different cranes, depending on the size of the cranes (B_i and K_i in Figure 2). The means and standard deviations of the distance d are calculated as $\mu_d = (\mathrm{L} + 2\mathrm{d}_{\min})/4$ and $\sigma_d = (\mathrm{L} - 2\mathrm{d}_{\min})/4\sqrt{3}$, respectively. The outer wheel of the first crane near the second crane is always located at the maximum bearing moment value position on the bearing moment influence line (point C) (Figure 3). The influence line ordinate of the first crane is expressed as $y_1 = y_{1,\max} = (\mathrm{L}-\mathrm{K}_1)/2$. The influence line ordinate of the second crane y_2 follows a piecewise uniform distribution:

$$y_2 = \begin{cases} \frac{1}{2}(\mathrm{L} - 2d - \mathrm{K}_2) & d \in \left[\mathrm{d}_{\min}, \frac{\mathrm{L}}{2} - \mathrm{K}_2\right) \\ \frac{1}{4}(\mathrm{L} - 2d) & d \in \left[\frac{\mathrm{L}}{2} - \mathrm{K}_2, \frac{\mathrm{L}}{2}\right] \end{cases} \quad (7)$$

These two stages are shown in Figures 3(a) and 3(b), respectively. If the case probability shown in Figure 3(a) is calculated as $P_1 = 1 - 2\mathrm{K}_2/(\mathrm{L}-2\mathrm{d}_{\min})$, and the case probability shown in Figure 3(b) is calculated as $P_2 = 2\mathrm{K}_2/(\mathrm{L}-2\mathrm{d}_{\min})$, for $P_1 + P_2 = 1$, the influence line ordinates y_2 can be transformed as

$$\begin{aligned} y_2 &= \frac{P_1}{2}(\mathrm{L} - 2d - \mathrm{K}_2) + \frac{P_2}{4}(\mathrm{L} - 2d) \\ &= \frac{(1+P_1)\mathrm{L}}{4} - \frac{P_1\mathrm{K}_2}{2} - \frac{(1+P_1)d}{2} \end{aligned} \quad (8)$$

The mean and standard deviation of y_2 can be calculated as

$$\begin{aligned} \mu_{y_2} &= \frac{(1+P_1)\mathrm{L}}{4} - \frac{P_1\mathrm{K}_2}{2} - \frac{(1+P_1)\mu_d}{2} \\ &= \frac{\mathrm{L} - 2\mathrm{d}_{\min} - \mathrm{K}_2}{4} - \frac{\mathrm{K}_2(\mathrm{L} - 2\mathrm{d}_{\min} - 2\mathrm{K}_2)}{2(\mathrm{L} - 2\mathrm{d}_{\min})} \\ &= \frac{(\mathrm{L} - 2\mathrm{d}_{\min})}{4} - \frac{3\mathrm{K}_2}{4} + \frac{\mathrm{K}_2^{\,2}}{(\mathrm{L} - 2\mathrm{d}_{\min})} \end{aligned} \quad (9)$$

$$\sigma_{y_2} = \frac{(1+P_1)\sigma_d}{2} = \frac{\mathrm{L} - 2\mathrm{d}_{\min} - \mathrm{K}_2}{4\sqrt{3}} \quad (10)$$

The crane load combination action S applied by multiple cranes on the crane beam is a function of the crane loads and their corresponding influence line ordinates. Probability distributions and moment parameters of these independent variables are known. To calculate reliability index, these variables can be considered as independent random variables, or simplified into a comprehensive variable S for convenience:

$$\begin{aligned} &S \\ &= \{(y_1 Q_{\max,T} + y_2 Q_{0.5,\max,\tau}) \, or \, (y_1 Q_{\max,T} + y_2 Q_{0,\max,\tau})\} \end{aligned} \quad (11)$$

All random variables in (11) are assumed as mutually independent and uncorrelated. The S distribution type depends on the distribution types of these independent variables. Considering the fact that crane load plays a decisive role in the distribution type of the combination action, the

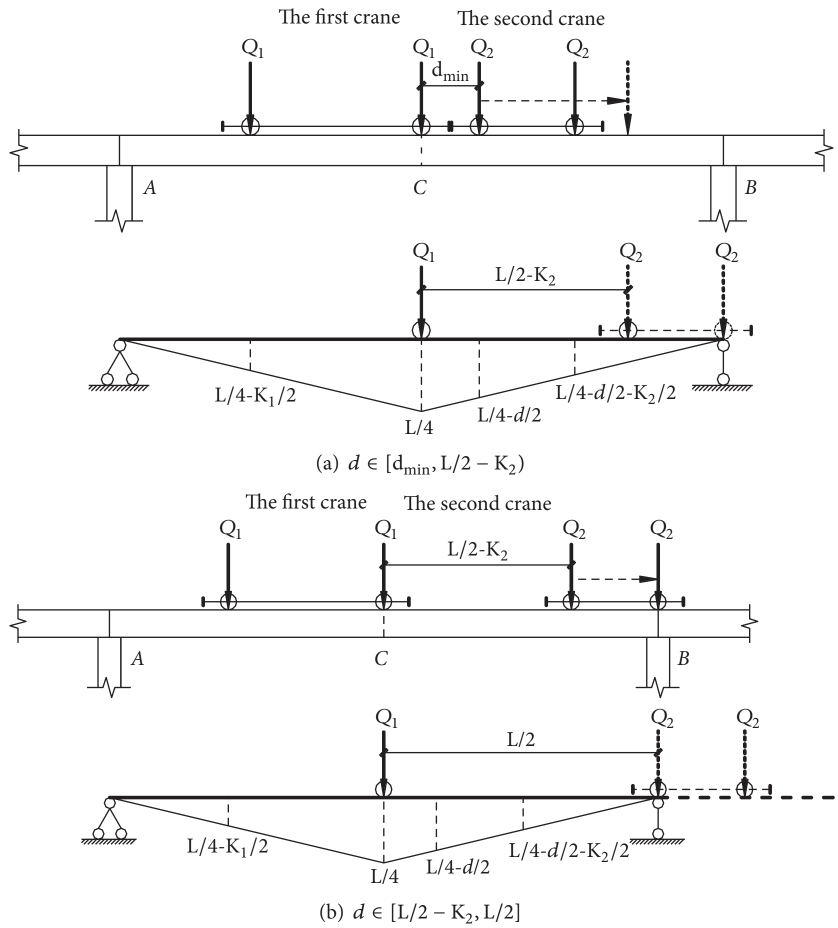


Figure 3: Schematic diagram showing the two stages function of the influence line ordinate y_2.

Gumbel (type I) distribution is assumed as the distribution type, which simplifies the type of crane load combination action S for FORM analysis [5]. Distribution parameters are determined according to the error transfer formula. The assumed distribution and calculated parameters are evaluated in Section 3.2.

$$\mu_S = \left\{\left(y_1\mu_{Q_{\max,T}} + \mu_{y_2}\mu_{Q_{0.5,\max,\tau}}\right) or \left(y_1\mu_{Q_{\max,T}} + \mu_{y_2}\mu_{Q_{0,\max,\tau}}\right)\right\} \quad (12)$$

$$\sigma_S = \left\{\left({y_1}^2{\sigma_{Q_{\max,T}}}^2 + {\mu_{y_2}}^2{\sigma_{Q_{0.5,\max,\tau}}}^2 + {\mu_{Q_{0.5,\max,\tau}}}^2{\sigma_{y_2}}^2\right)^{0.5} or \left({y_1}^2{\sigma_{Q_{\max,T}}}^2 + {\mu_{y_2}}^2{\sigma_{Q_{0,\max,\tau}}}^2 + {\mu_{Q_{0,\max,\tau}}}^2{\sigma_{y_2}}^2\right)^{0.5}\right\} \quad (13)$$

3. Assessment of the Assumed Distribution and Calculated Parameters of S

In Section 2, the maximum value distribution of the crane loads during the design reference period is established. Using the modified Turkstra method, the probability model of multiple crane combination actions on the crane beam is improved. In this section, these expression formulas distributions will be estimated by the POT and Monte Carlo methods (much more precise theory but without expression formula method), respectively.

3.1. Checking the Maximum Crane Load Value Distribution Using the Peaks-Over-Threshold Method. As a discontinuous stochastic process through time, crane load should be regarded as Poisson rectangular wave if the load amplitude changes to a rectangular form during the design period and the amplitude is constant for each time interval. This process assumes that both the amplitude change (k) during the design period and action time interval ($t_i = \tau_i$) are random variables. The average number of action changes per unit-time is represented as $\lambda = 1/\tau$.

Table 2: Statistics of combination actions.

Crane load category	Experimental results			Calculated results			Mean relative error	STD relative error
	Mean	STD (Standard Deviation)	Skewness	Median	Mean	STD (Standard Deviation)		
vertical loads	202.87	18.91	0.28	202.01	200.11	22.66	0.014	0.198
horizontal forces	26.86	7.64	0.98	25.73	28.04	7.90	0.044	0.034

The magnitude of the maximum crane load is a nonnegative value in each operating time, whose probability distributions in different time intervals are identical. Maximum crane load values during each action time interval (τ_i) are changeless, and the probability distributions in each τ_i are the same. The number of action changes k during the design reference period follows a Poisson process [22]

$$P[N(T)=k]=\frac{(\lambda T)^k}{k!}\exp(-\lambda T) \tag{14}$$

If the arbitrary point-in-time value probability distribution is $F_{Q_\tau}(x)$, the mean upcrossing rate at any threshold x per unit-time is

$$v^+(x)=\lambda\left(1-F_{Q_\tau}(x)\right) \tag{15}$$

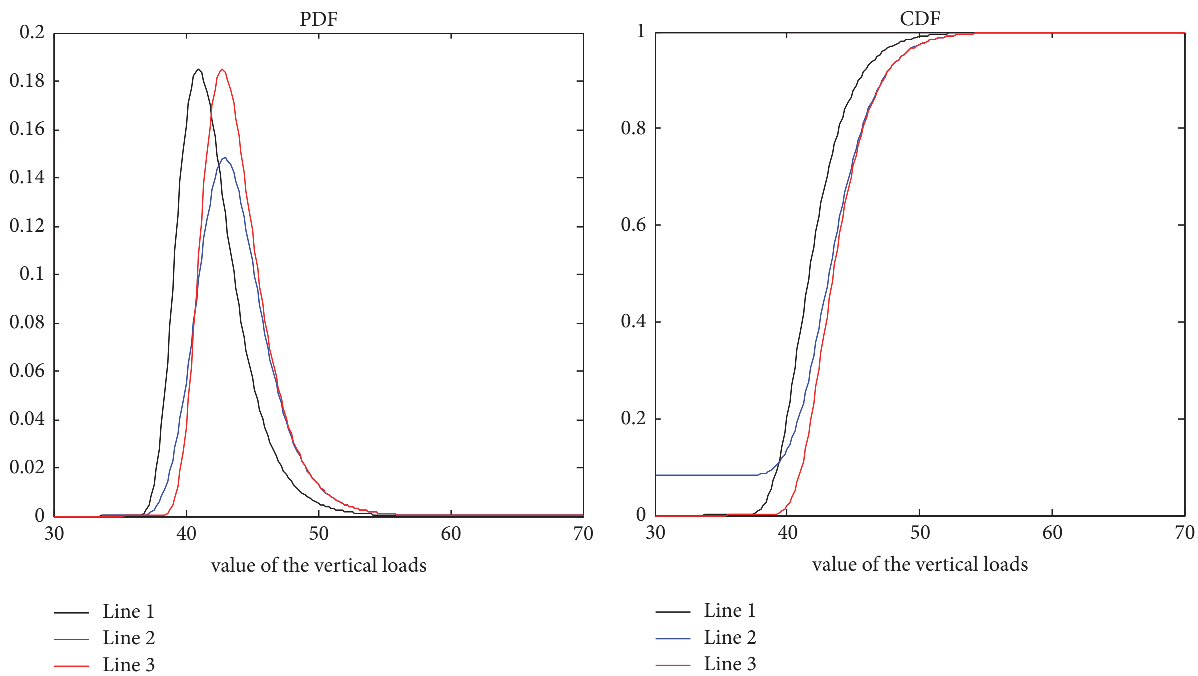
Invoking the Poisson assumption of upcrossings, the extreme value distribution during the design reference period T is calculated in terms of a generalized extreme value (GEV) distribution [23]. The maximum crane load is a pulse-type load not a continuous-type load during each action time interval (τ_i); the cumulative distribution function (CDF) of the maximum crane load during the design reference period $F_{Q_T}(x)$ is

$$\begin{aligned} F_{Q_T}(x) &= \text{Prob}\left\{Q_{\max}(T)\le x\right\}=\exp\left[-v^+(x)T\right] \\ &= \exp\left[-\lambda T\left(1-F_{Q_\tau}(x)\right)\right] \end{aligned} \tag{16}$$

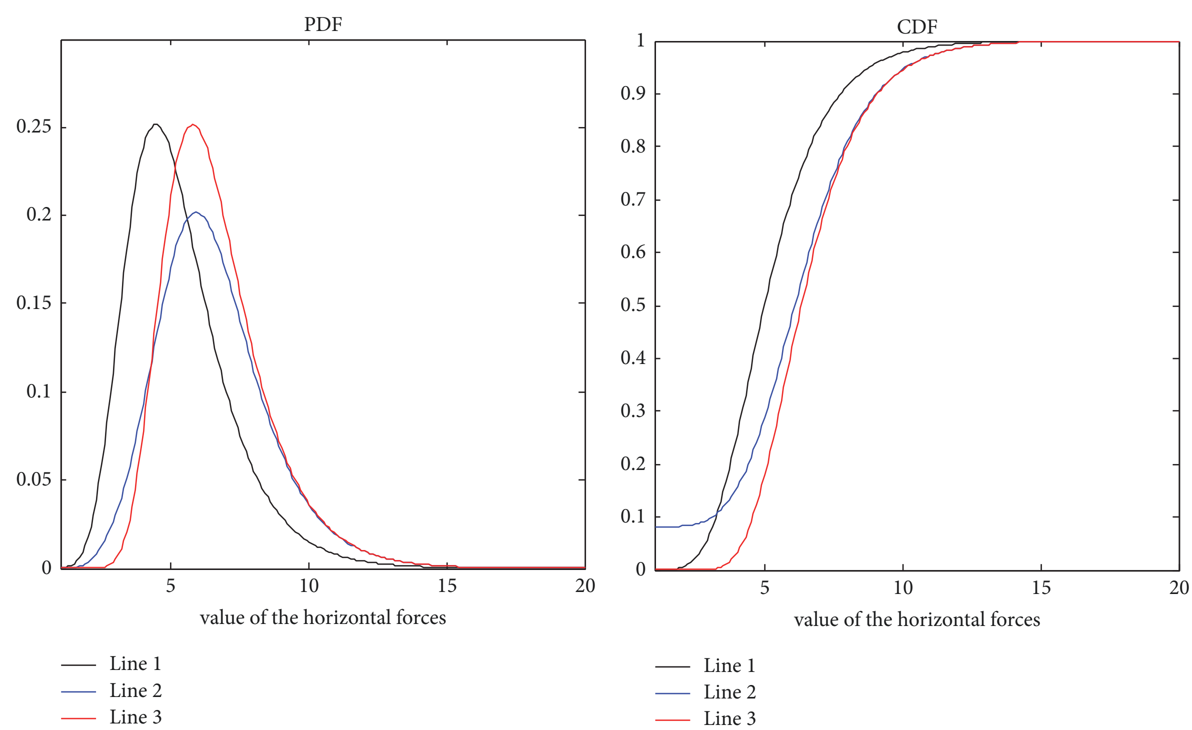
With (16), the maximum value CDFs of the vertical load and horizontal force calculated by (5) and (6) can be evaluated. Here a crane load with a medium working level (A5) and Q_{HK}=5t is chosen as an example for analysis. With this crane designed by the Dalian Lifting Machinery Group, the corresponding performance parameters are l = 19.5 m, B = 4.77 m, K = 4 m, G = 13.9 t, g = 1.698t, and W_C = 69 kN [24]. The CDFs and PDFs (Probability Distribution Functions) of the arbitrary point-in-time value and maximum value during the design reference period are determined by the maximum value method in Section 2.3. The POT method for vertical load and horizontal force is shown in Figure 4. Other crane cases demonstrate similar results.

In Figure 4, the distribution of the arbitrary point-in-time value is plotted in (2) and (3) with the statistical parameters listed in Table 1 (the black line). The distribution of the maximum value during the design reference period T = 50 years is plotted using (5) and (6) with the maximum value method (the red line, using the stationary binomial random process) and (16) with the POT method (the blue line, using the Poisson rectangular wave process). The maximum value is larger than the arbitrary point-in-time value for the same guarantee rate. The maximum value method and the POT method for the tail of the distribution functions are in approximate agreement. The maximum value method has the highest quotient representing the most reliable result.

3.2. Checking Crane Load Combination Distribution Actions Distribution Using Monte Carlo Simulation. To estimate the assumed distribution and the calculated parameters of the crane load combination action S, some adequate sample data are directly collected from the random data using the Monte Carlo simulation (MCS) method. Considering the probability distributions of these random variables in (11) and the actual cases in Figure 3, as well as using the example crane mentioned in Section 3.1, let two identical cranes act on a beam with a span of 12 m. Through calculations, the reduction factors for the arbitrary point-in-time values of the vertical loads and the horizontal forces with the “empty load” considering about A5 working levels here are 0.61 and 0.25, respectively. We wrote a MATLAB program to obtain the combination action date. To ensure simulation error is less than 0.005, the simulation must be larger than 1537 times [2]. For 10000 times simulation and 10000 empirical samples, the empirical histograms and CDFs are shown in Figure 5. The assumed distributions (PDFs and CDFs) with the calculated parameters are shown in Figure 5. Using the Chi-square goodness-of-fit test, the data does not reject the null hypothesis of the Gumbel (type I) distribution at the default 5% significance level. Distribution parameters of the random experimental combination actions and the calculated results are summarized in Table 2. For the comparison results of the vertical load in Figure 5(a), when the crane load combination action S is less than 225, the probability of S appearing is slightly higher than in the Gumbel distribution mode; and when it is more than 225, the probability is slightly lower. That means with the improved load model here, the calculated value of reliable indicator is slightly lower than actual value with smaller load values (conservative for the project), and slightly higher with larger load values (not conservative for the project). With the conservative reliability calculation method of FOSM [23], and the less deviation of the distribution parameters (in Table 2), the final calculation should be acceptable. For the comparison results of the horizontal force in Figure 5(b), the improved load model and the actual value are almost consistent. So, the Gumbel (type I) distribution and the distribution parameters determined in Section 2.4.3 for the crane load combination actions are satisfactory.

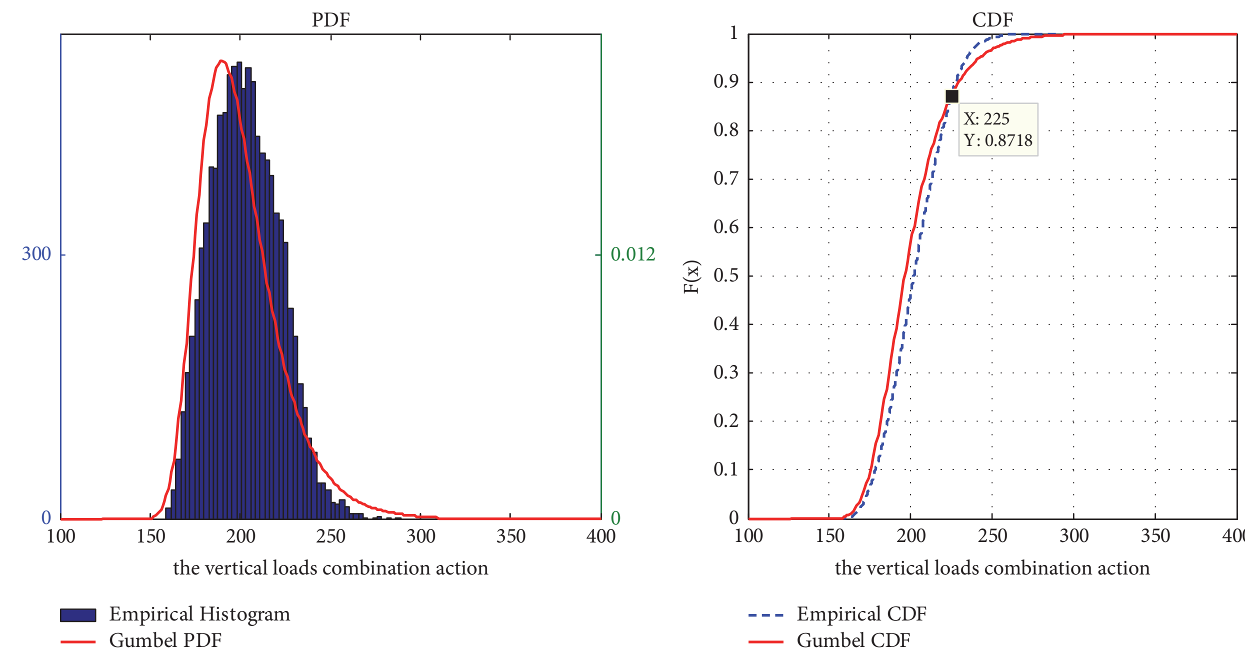


(a) Validation of the vertical load model

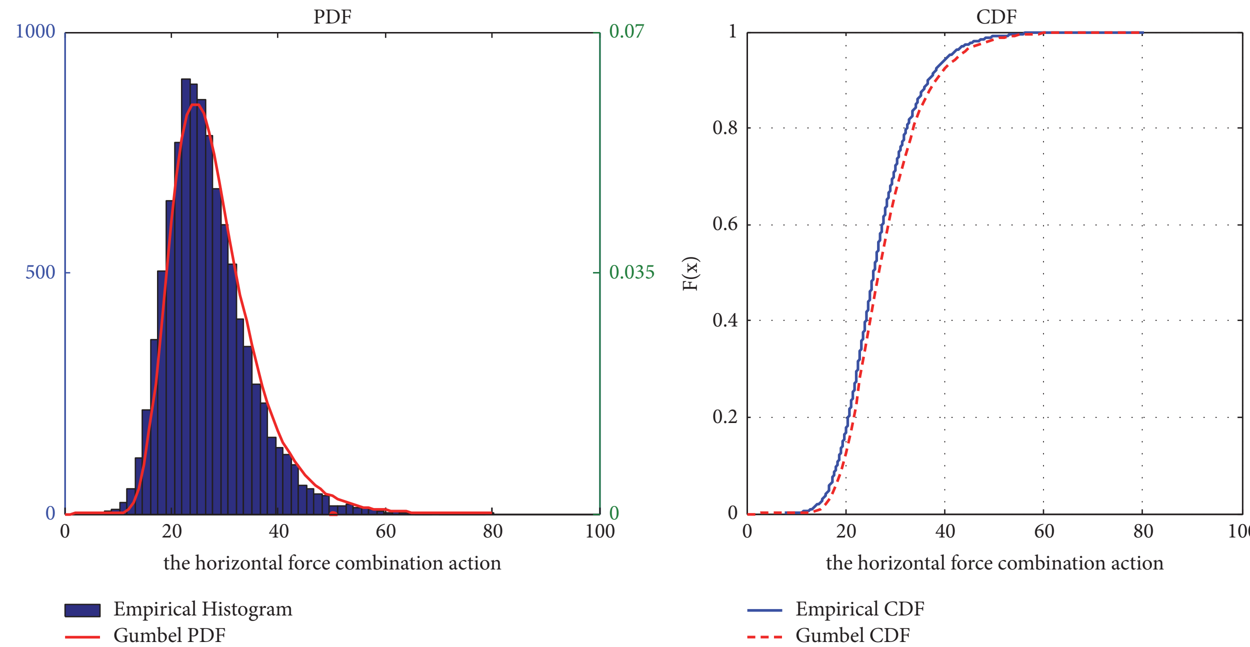


(b) Validation of the horizontal force model

FIGURE 4: CDF and PDF of the arbitrary point-in-time distribution, the maximum value distribution during the design reference period determined by (a) the maximum value method and (b) the POT method for the vertical load and the horizontal force (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article). *Note*. Line 1: distribution of the arbitrary point-in-time value. Line 2: distribution of the maximum value determined by POT method. Line 3: distribution of the maximum value determined by the maximum value method.



(a) The comparison results of the vertical load



(b) The comparison results of the horizontal force

FIGURE 5: The distributions of multiple crane load combination actions simulated using the MCS method (empirical histogram and CDF (the blue line)) and the approximate method described in Section 2 (Gumbel PDF and CDF (the red line)) for the (a) vertical load and (b) horizontal force (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

4. Code Design Standard Values and Quota Levels

China "load code for the design of building structures" [4] provides the design load and their actions for structure design and engineering projects. The load code specifies the value principle for crane load and multiple crane load combination actions for runway beam design. For overhead traveling cranes, the nominal maximum wheel pressure W_C provided by the crane supplier is taken as the design standard vertical load value. W_C is calculated as the sum of the bridge weight, the rated capacity, the trolley weight, and the actual maximum load effect (Figure 1). Considering the induced vertical impact or vibration force, W_C is increased by a dynamic factor, about 1.05 for A1-A5 working level cranes and 1.1 for A6-A8 working level cranes. The design standard value of the longitudinal horizontal force is calculated as 10% of the maximum wheel loads of the crane. The transverse horizontal force for electrically powered trolleys is calculated by the following percentages for the sum of the rated capacity and the weight of the hoist and trolley [4].

For soft hook cranes:	$Q_{HK} \leq 10t$	12%
	$10t < Q_{HK} < 75t$	10%
	$Q_{HK} \geq 75t$	8%
For hard hook cranes:		20%

When calculating multiple crane load combination actions for beam design, two cranes simultaneously located in the worst-case positions are considered. Moreover, considering the occurrence probability in this case, the combination results are reduced by a coefficient, approximately 0.9 for A1-A5 working level cranes and 0.95 for A6-A8 working level cranes.

With the specified crane load and combination principles for runway beam design, characteristic design values can be calculated. With the determined distribution of crane load and multiple crane load combination actions, the design values can be evaluated with a quote level for exceeding probability towards an unfavourable value during the reference period [25]. Considering the example in Section 3, the standard design values of the vertical load and the transverse horizontal force reach 99.98% and 80.69% of quota levels, and the design crane load combination actions of the vertical load and the transverse horizontal force reach 99.9% and 97.43% of quota levels. The characteristic value of vertical load is excessively conservative. The standard value of the horizontal force is somewhat excessive and hazardous because forces caused by skewing of the crane in relation to its movement are not considered. However, the crane load combination action is much safer and conservative.

5. Summary and Conclusion

Crane load, as a two-dimensional stochastic process, is analysed using probability methods. The arbitrary point-in-time value distribution of the crane load values varying in time follow the Gumbel (type I) distribution improved with engineering surveys and K-S test results. The maximum value distribution of the crane load values during the design reference period is determined as the Gumbel (type) distribution using the block maxima method of the stationary binomial random process hypothesis and evaluated with the POT method for the filtration Poisson process. The maximum value is larger than the arbitrary point-in-time value with the same guarantee rate level.

The probability distribution of multiple crane load combination actions is taken as Gumbel (type) distribution using the modified Turkstra rule and the influence line methods. The probability distribution is accepted by evaluation with the Monte Carlo simulations method and the Chi-square goodness-of-fit test.

The model parameters of the above distribution with the used assumptions and the chosen value parameters are determined by statistical surveys and load experiments in China. If some of the used assumptions are modified or some of the different chosen value parameters are changed with reliable survey results, it can be calculated with the same method.

After crane load probability models improved, the design standard values specified in China load code for runway beam design are assessed with probability significance. With high quota levels, the specified crane load and combination actions are conservative and redundant for design. For the standard codes used in China, the combination coefficients to calculate the design value of the multiple crane load combination actions could be reduced appropriately after analysis of the design reliability calibration results of the crane beams and columns with different plant spans, component sizes, various load combinations, and crane working levels. It will be discussed in further research and another paper.

Data Availability

The data used to support the findings of this study are included within the article and [4].

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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