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RESEARCH

Global sensitivity of reliability for the crane runway girder

Ngoc-Long Tran[1] · Trong-Ha Nguyen[1]

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Abstract
The crane runway girder is an indispensable structure in industrial buildings with cranes, which is responsible for transferring the load from the crane and itself loads. The geometry properties, materials properties, and load input parameters are random variables in practice. Therefore, it must ensure the necessary reliability. This study presented the reliability assessment of the crane runway girder. To achieve the goal, the deterministic model is built based on the design approach for the crane runway girder according to EC-3. Meanwhile, the deterministic model with random input parameters has been called a stochastic model. Random variables for input design parameters are considered in the proposed procedure. The reliability assessment of the crane runway girder was based on the stochastic model and Monte Carlo simulation method. Finally, the effect of random input parameters investigated based on global Sobol sensitivity analysis was also presented.

Keywords Reliability assessment · Global sensitivity · Crane runway girder · Monte Carlo simulation method · Crane girder

Introduction

The crane runway girder is designed according to Euro-code 3 Part 6 (EC3-P6) (1993-3-1, 2006), BS 5950 (5950), and some steel structures design standards. The safe condition of the crane runway girder must be satisfied: (I) ultimate limit state and (II) serviceability limit state with the load from the crane and itself loads. On the other hand, the geometry properties, materials properties, and load input parameters are random variables in practice. Therefore, it must ensure the necessary reliability.

Reliability-based design is important for structural safety, and it was included in the standards, such as ISO 2394:2012, JB50153-92, and BS 5760-0:2014. Especially, in the steel structure field, there are many researchers interested. The reliability assessment of frame steel considering semi-rigid connections using the Monte Carlo simulation algorithm was proposed in (Ha, 2019). Also, using Monte Carlo simulation for reliability assessment of steel plane frame's buckling strength considering semi-rigid connections was presented in (Tran & Nguyen, 2020). Meanwhile, a reliability analysis of H-section steel columns under blast loading was published by (Hadianfard et al., 2018). A time-dependent reliability assessment of a continuous i-shaped steel beam considering corrosion effects with climate scenarios was conducted (Nguyen et al., 2022). The nonlinear integrated analysis model, the semi-analytical simulation method employed for system reliability assessment, the development processes of the RID format, and the design application of the RID formula and curves were presented in (Li & Li, 2004). Moreover, it can also be found in the following studies (António & Hoffbauer, 2017; Gündel et al., 2014; Hadianfard et al., 2018; Li & Li, 2004; Malekizadeh et al., 2022; Mamuda et al., 2018; Melchers & Beck, 2018; Nguyen & Nguyen, 2022; Okasha, 2016).

Recently, studies on the effect of random input parameters investigated based on global Sobol's sensitivity indices have been many researchers interested can be seen in (Kala, 2009; Morio, 2011; Nguyen, 2020; Nguyen & Nguyen, 2020). However, to the best of our knowledge, no studies have been presented yet on the effect of input parameters on the reliability of the crane runway girder.

This study presented the reliability assessment of the crane runway girder. The deterministic model is built based on the design approach for the crane runway girder according

✉ Trong-Ha Nguyen
trongha@vinhuni.edu.vn

Ngoc-Long Tran
longtn@vinhuni.edu.vn

[1] Department of Civil Engineering, Vinh University, Vinh 461010, Vietnam

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to EC-3. Meanwhile, the deterministic model with random input parameters has been called the stochastic model. Random variables for input design parameters are considered in the proposed procedure. The reliability assessment of the crane runway girder was based on the stochastic model and Monte Carlo simulation method. Finally, the effect of random input parameters investigated based on global Sobol sensitivity analysis has been also presented.

Material and methodologies

In this study, the design of the crane runway girder is basically according to Euro-code 3 Part 6 (EC3-P6) (1993-3-1, 2006). Which, the design of the crane runway girder is to satisfy the safety conditions due to vertical wheel loads, transverse loads, fatigue, and impact forces. Considering crane details are shown in Fig. 1.

Calculated vertical wheel loads and horizontal loads

Vertical wheel loads

Calculated vertical wheel loads of the crane girder include the unloaded crane and loaded crane according to table 2.2 of Euro-code-1 Part 3. Vertical wheel loads in unloaded crane case

$$\sum Q_{r,(\min)} = \frac{1}{2}\varphi_1 Q_{c1} + \varphi_1 Q_{c2},$$

$$\sum Q_{r,\min} = \frac{1}{2}\varphi_1 Q_{c1}. \tag{1}$$

Vertical wheel loads in loaded crane case

$$\sum Q_{r,(\max)} = \frac{1}{2}\varphi_1 Q_{c1},$$

$$\sum Q_{r,\max} = \frac{1}{2}\varphi_1 Q_{c1} + \varphi_1 Q_{c2} + \varphi_2 Q_{h,k}. \tag{2}$$

The vertical wheel loads on the crane girder and crane runway girder are shown in Fig. 1.

Horizontal loads

Calculated horizontal loads of the crane girder include those caused by the acceleration and deceleration of the crab. Calculated the horizontal loads according to Euro-code 1—Part 3: 2.7.2. It can be rewritten as follows:

Drive force K

$$K = \mu \sum Q *_{r,\min}, \tag{3}$$

where $\sum Q *_{r,\min} = m_w Q_{r,\min}$; μ and m_w are friction factor and number of single wheel drivers, respectively.

$$\xi_1 = \frac{\sum Q_{r,\max}}{Q_r},$$

where

$$Q_r = \sum Q_{r,\max} + \sum Q_{r,(\max)}, \tag{4}$$

$$\xi_2 = 1 - \xi_1,$$

$$l_s = \left(\xi_1 - 0.5\right) \cdot l,$$

$$M = K \cdot l_s. \tag{5}$$

Transverse loads $H_{T,i}$ has been determined

$$H_{T,1} = \varphi_5 \xi_2 \frac{M}{a}; H_{T,2} = \varphi_5 \xi_1 \frac{M}{a}. \tag{6}$$

Definition of transverse loads $H_{T,i}$ is shown in Fig. 2.

Fatigue loads

According to Euro-code -1 Part 3, 2.12.1(4), the fatigue loads have been determined.

$$Q_{e,i} = \varphi_{fat} \cdot \lambda_i \cdot Q_{\max,i}. \tag{7}$$

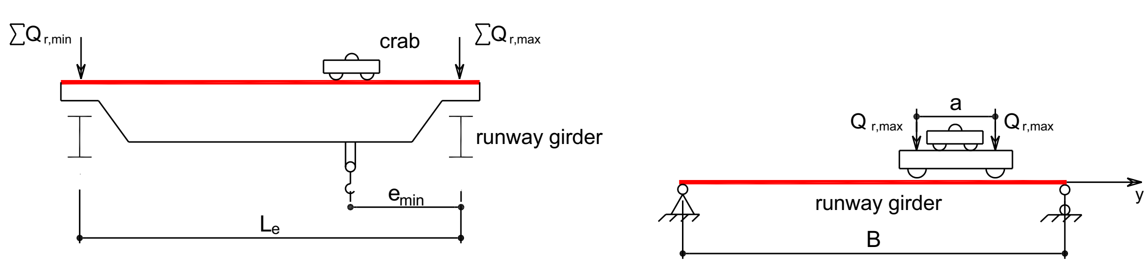

Fig. 1 Calculation diagram of the vertical wheel loads

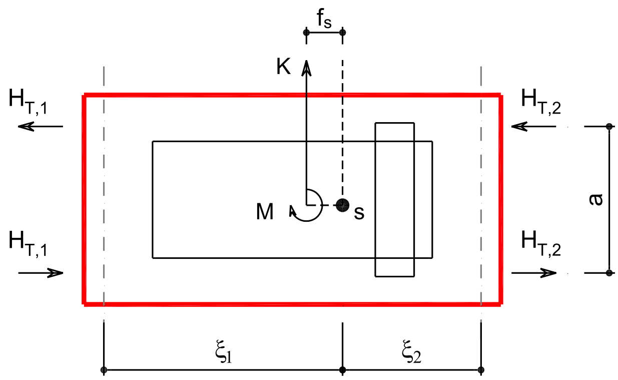

Fig. 2 Calculation diagram of the transverse loads $H_{T,i}$

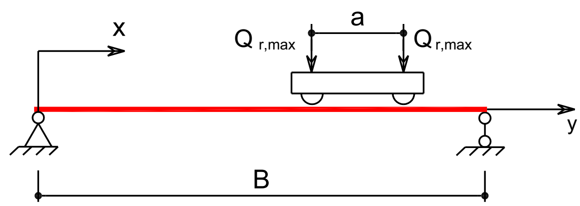

Fig. 3 Calculation diagram of the condition that deduces the position of the vertical wheel loads for maximum bending moments

Internal forces and moments of the crane runway girder

The internal forces and moments of the crane runway girder were calculated with influences lines. The positions of loads for maximum bending moments and shear forces are shown in Fig. 3. It is determined as follows:

$$A = \frac{(2B - a) - 2x}{B},$$

$$M(x) = A \cdot x, \tag{8}$$

max $M(x) \leftrightarrow \dot{M}(x) = 0$ is the condition that deduces the position of the vertical wheel loads for maximum bending moments (x).

Bending moments $\left(M_{y,k} \text{and} M_{z,k}\right)$

Bending moments of the crane runway girder were calculated with types of loads: self-weight, vertical wheel loads, and transverse loads at x.

Bending moments $M^{w}_{y,k}$ in a self-weight case

$$M^{w}_{y,k} = \frac{g_k B}{2} x - \frac{g_k x^2}{2}. \tag{9}$$

Bending moments $M^{wh}_{y,k}$ in vertical wheel loads' case

$$\max M^{wh}_{y,k} = Q_{r,\max}\left(\eta_1 + \eta_2\right) \cdot B,$$

$$\min M^{wh}_{y,k} = 0. \tag{10}$$

Bending moments $M^{tr}_{z,k}$ in transverse loads' case

$$\min M^{tr}_{z,k} = \left(H_{T,2} \cdot \eta_1 + H_{T,2}\eta_2\right) \cdot B,$$

$$\max M^{tr}_{z,k} = \left(H_{T,2} \cdot \eta'_1 + H_{T,2}\eta'_2\right) \cdot B, \tag{11}$$

where g_k is the self-weight of the crane runway girder. $\eta_1, \eta_2, \eta'_1, \eta'_2,$ and$B$ are shown in Fig. 4

Shear forces $V_{z,k}$ and $V_{y,k}$

The shear forces of the crane runway girder were also calculated with types of loads: self-weight, vertical wheel loads, and transverse loads at x.

Shear force $V^{w}_{z,k}$ in a self-weight case

$$V^{w}_{z,k} = \frac{g_k B}{2} - g_k x. \tag{12}$$

Shear force $V^{wh}_{z,k}$ in vertical wheel loads' case

$$\max V^{wh}_{z,k} = Q_{r,\max}\left(\epsilon_1 + \epsilon_2\right),$$

$$\min V^{wh}_{z,k} = Q_{r,\max}\left(\epsilon'_1 + \epsilon'_2\right). \tag{13}$$

Shear force $V^{tr}_{y,k}$ in transverse loads' case

$$\min V^{tr}_{y,k} = \left(H_{T,2}\epsilon_1 + H_{T,2}\epsilon_2\right),$$

$$\max V^{tr}_{y,k} = \left(H_{T,2}\epsilon'_1 - H_{T,2}\epsilon'_2\right), \tag{14}$$

where, $\epsilon_1, \epsilon_2, \epsilon'_1,$ andϵ'_2 are shown in Fig. 5

Cross-section resistance of the crane runway girder

According to EC3-P1:5.1 and EC3-P1:6.2.6, shear resistance of the web (z-axis) must be satisfied

$$\frac{d}{t_w} \leq 60,$$

$$\frac{V_{z,Sd}}{V_{z,Rd}} \leq 1.0, \tag{15}$$

where $V_{z,Sd} = \gamma_G G_k + \gamma_Q Q_k; V_{z,Rd} = A_V \frac{f_y/\sqrt{3}}{\gamma_M}.$

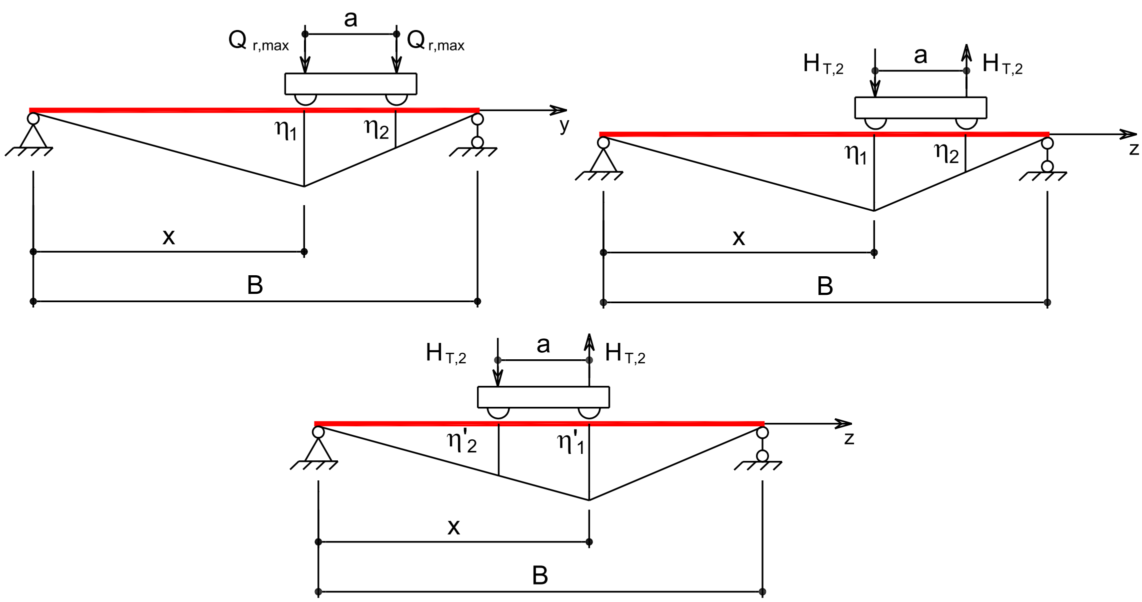

Fig. 4 Calculation diagram of the bending moments $\left(M_{y,k}\text{and}M_{z,k}\right)$

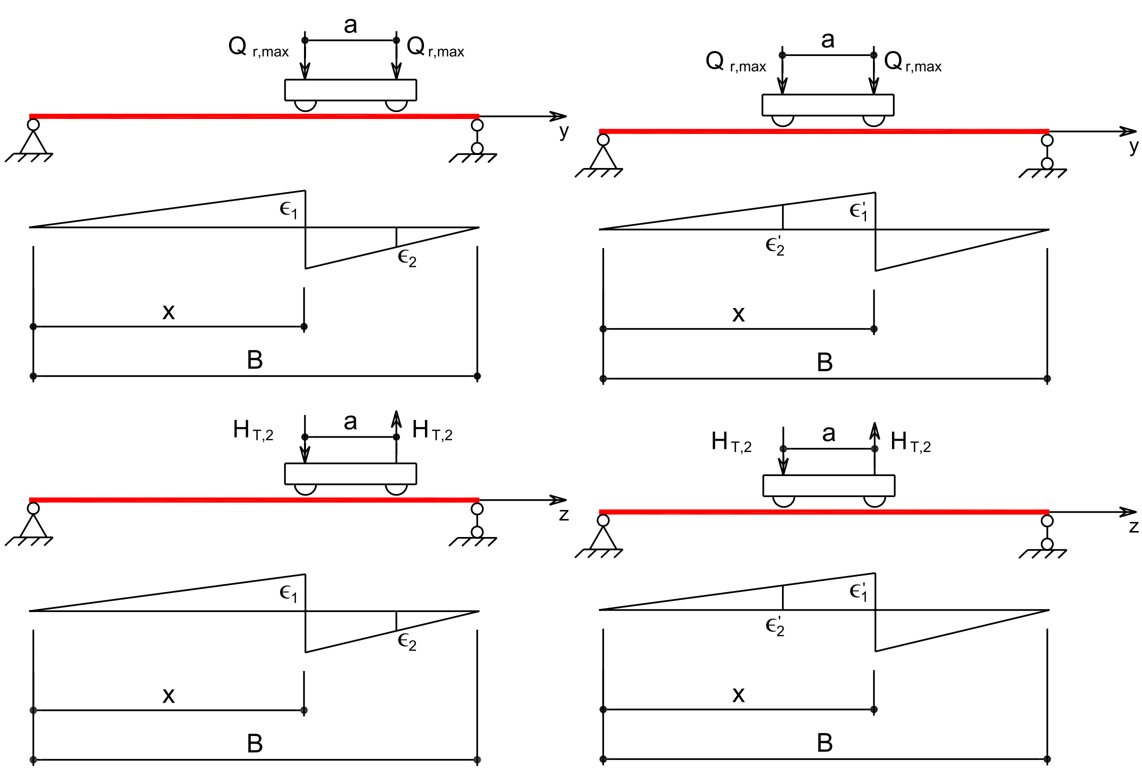

Fig. 5 Calculation diagram of the shear forces $V_{z,k}$ and $V_{y,k}$

According to EC3-P1:6.2.6, shear resistance of the top flange (y-axis) must be satisfied

$$\frac{\max V_{y,Sd}}{V_{y,Rd}} \le 1.0, \tag{16}$$

with $\max V_{y,Sd} = \gamma_Q Q_k$; $V_{z,Rd} = A_{TV}\frac{f_y/\sqrt{3}}{\gamma_M}$.

And shear resistance due to torsion

$$\frac{\tau_{V,Ed}}{\frac{\left(f_y/\sqrt{3}\right)}{\gamma_M}} \le 1.0;\text{where}\tau_{V,Ed} = \frac{M_{t,Sd}\cdot t}{I_t}. \tag{17}$$

Interaction between normal and shear forces according to EC3-P1:6.2.6(2), 6.2.7, and 6.2.8 has the form.

$$\frac{V_{Ed}}{0.5V_{pl,T,Rd}} \le 1.0, \tag{18}$$

where $V_{T,Rd} = A_V\frac{\left(f_y/\sqrt{3}\right)}{\gamma_M}$; $V_{pl,T,Rd} = \sqrt{1-\frac{\tau_{V,Ed}}{1.25\cdot\frac{\left(f_y/\sqrt{3}\right)}{\gamma_M}}}V_{T,Rd}$.

Bending and axial forces

$$\frac{N_{Sd}}{A_{FT}\cdot f_{y,d}} + \frac{M_{y,Sd}}{W_{el,y}\cdot f_{y,d}} + \frac{M_{z,Sd}}{W_{el,z}\cdot f_{y,d}} \le 1.0. \tag{19}$$

According to EC3-P1:6.2.4 verification for transverse loads

$$\frac{N_{sd}}{A_{TF,\text{net}}\cdot f_{y,d}} \le 1.0\text{with}A_{TF,\text{net}} = A_{TF} - \Delta A. \tag{20}$$

According to EC3-P9:8 (2) and EC3-P6:9.4.1 (4), fatigue assessment of the crane runway girder with self-weight and wheel loads for the top and bottom flange must be satisfied

$$\left[\frac{\gamma_{Ff}\cdot\Delta\sigma_{E2}}{\frac{\Delta\sigma_c}{\gamma_{Mf}}}\right]^3 + \left[\frac{\gamma_{Ff}\cdot\Delta\tau_{E2}}{\frac{\Delta\tau_c}{\gamma_{Mf}}}\right]^5 \le 1.0, \tag{21}$$

where $\Delta\sigma_{E2}$ and $\Delta\tau_{E2}$ are normal stresses at the top flange and shear stresses in the web, respectively.

According to EC3-P6:9.1.4, the fatigue assessment is necessary if the number of load cycles of 50% of the full payload is more than 10,000 cycles. In this study, the fatigue assessment process of the crane runway is based on the basic nominal stress range.

According to EC3-P9: (2)

$$\gamma_{Ff}\cdot\Delta\sigma_{E2} \le \frac{\Delta\sigma_c}{\gamma_{Mf}}. \tag{22}$$

According to EC3-P6: 9.4.1

Table 1 The coefficients of the equation for fatigue assessment

Coefficient	Reference sources
$\gamma_{Ff} = 1.00$	EC3-P6:9.3(1)
$\gamma_{Mf} = 1.15$	EC3-P9: Table 3.1
$\lambda = 0.794$ for normal stresses	EC1-P9: Table 2.12
$\lambda = 0.871$ for shear stresses	EC1-P9: Table 2.12
$\Phi_{\text{fat}} = 1.10$	EC1-P3:2.12.1(7)

$$\Delta\sigma_{E2} = \lambda\Phi_{\text{fat}}\Delta\sigma_P. \tag{23}$$

According to EC1-P3:2.12.1, stresses $\Delta\sigma_{E2}$ are determined from the fatigue loads for normal and shear stresses

$$Q_{e,i} = \lambda\Phi_{\text{fat}}Q_{\max,i}. \tag{24}$$

The coefficients and reference sources are shown in Table 1

Monte Carlo simulation

The Monte Carlo simulation technique was proposed by Melchers and Beck (2018). Estimates of the reliability can be rewritten as follows.

$$P_f = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{I(x,y)f_R(x)f_Q(y)}{k_{XY}(x,y)}k_{XY}(x,y)dxdy, \tag{25}$$

where, $k_{XY}(x,y)$ is important sampling density. This integral can be estimated by the sum of the discrete values as follows:

$$\hat{P}_f = \frac{1}{N}\sum_{i=1}^{N}\frac{I\left(x_i,y_i\right)f_Q\left(y_i\right)}{f_{Q*}\left(y_i\right)}. \tag{26}$$

The variance of the sampled estimated significance is given by

$$\text{Var}\left(\hat{P}_f\right) = \frac{1}{N-1}\left\{\frac{1}{N}\sum_{i=1}^{N}\left[\frac{I\left(x_i,y_i\right)f_Q\left(y_i\right)}{f_{Q*}\left(y_i\right)}\right]^2 - \hat{P}_f^2\right\}. \tag{27}$$

Global sensitivity analysis

Global sensitivity is the method used for assessing the influence of input variables on the reliability of structures. The Sobol's approach is used in this study for assessing the influence of input variables on the reliability of structures. Sensitivity analysis is performed based on Monte Carlo simulations. The effects of input parameters are evaluated using Sobol's indies in space $\mathbb{R}^m$. In this work, algorithms and programs using MATLAB were developed and verified for evaluating the reliability of steel structures (Nguyen, 2020; Tran & Nguyen, 2021).

Reliability assessments

Safety conditions of the crane runway girder

The safety conditions of the crane runway girder were designed according to EC-3 (1993-3-1, 2006). Equations (15–24) can be summarized as follows:

$$M_{\mathrm{Saf}} = \begin{cases} \dfrac{d}{t_w} \leq 60 \\ \dfrac{V_{z,Sd}}{V_{z,Rd}} \leq 1.0 \\ \dfrac{\max V_{y,Sd}}{V_{y,Rd}} \leq 1.0 \\ \dfrac{\tau_{V,Ed}}{\frac{\left(f_y/\sqrt{3}\right)}{\gamma_M}} \leq 1.0 \\ \dfrac{V_{Ed}}{0.5V_{pl,T,Rd}} \leq 1.0 \\ \dfrac{N_{Sd}}{A_{FT} \cdot f_{y,d}} + \dfrac{M_{y,Sd}}{W_{el,y} \cdot f_{y,d}} + \dfrac{M_{z,Sd}}{W_{el,z} \cdot f_{y,d}} \leq 1.0 \\ \dfrac{N_{sd}}{A_{TF,net} \cdot f_{y,d}} \leq 1.0 \\ \left[\dfrac{\gamma_{Ff} \cdot \Delta\sigma_{E2}}{\frac{\Delta\sigma_c}{\gamma_{Mf}}}\right]^3 + \left[\dfrac{\gamma_{Ff} \cdot \Delta\tau_{E2}}{\frac{\Delta\tau_c}{\gamma_{Mf}}}\right]^5 \leq 1.0 \end{cases}, \tag{28}$$

where, M_{Saf} is the safety conditions based on EC-3.

Deterministic model

The deterministic model was built from safety conditions in Eq. 28. Where, the input parameters included geometrical properties, material properties, and total active load. The deterministic model can be written as

$$M_{\mathrm{Saf}} \leq 1.0. \tag{29}$$

Stochastic model

The stochastic model is developed based on the deterministic model. In this work, the input parameters $Q_{c1}, Q_{c2}, Q_{h,k}, B, b, h, t, s, f_y$, and $f_{y,d}$ are random variable (ω). The uncertain model can be written as

$$M_{\mathrm{Saf}}(\omega) \leq 1.0. \tag{30}$$

Information of crane runway example

This study used the deterministic design of the crane runway girder presented in (Pham, 2006) and is shown in Fig. 6. The input parameter is shown in Table 2. The program computer of the deterministic design was built based on MATLAB. The result of the computer program and its comparison with the result of (Pham, 2006) is shown in Table 2.

From Table 3, we can observe that the error is very small (< 3.0%). This result confirms the reliability of our program.

Convergence of the Monte Carlo simulation

The reliability assessment of the crane runway girder with input parameters is shown in Table 4. It shows the nominal and distributions of input parameters. The cross-section and loading have nominal and distributions based on

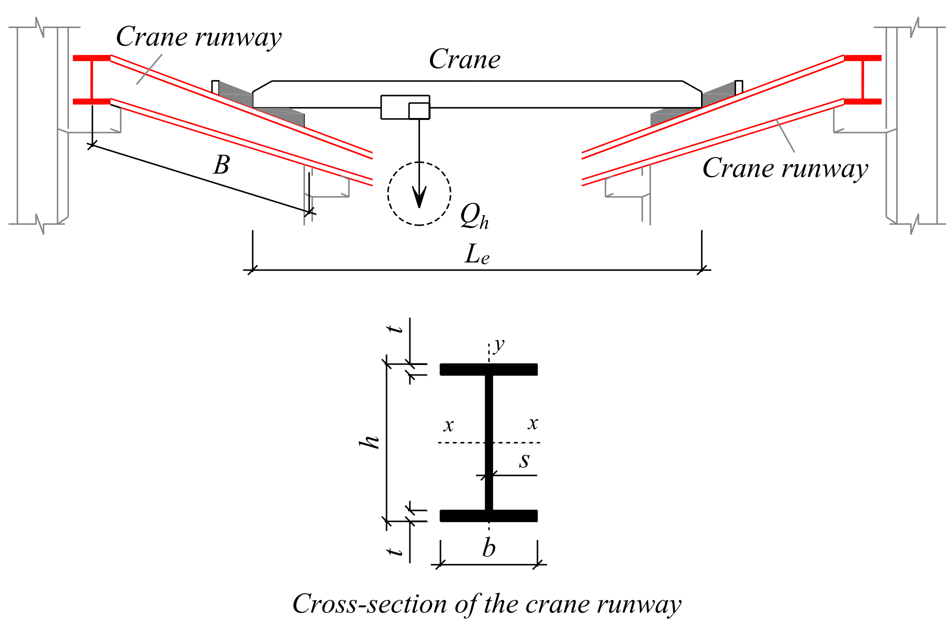

Fig. 6 A single girder overhead traveling crane

Table 2 Input parameters of crane runway example

Properties	Variables	Nominal	Units
Self-weight of the crane	Q_{c1}	60.00	(kN)
Self-weight of the crab	Q_{c2}	10.00	(kN)
Hoist load	$Q_{h,k}$	100.0	(kN)
Span length of the crane bridge	L_e	15.00	(m)
Span length of crane runway	B	9.00	(m)
Width of the crane runway girder section	b	0.25	(m)
Height of the crane runway girder section	h	0.45	(m)
Thickness-flange of the crane runway girder section	t	0.028	(m)
Thickness-web of the crane runway girder section	s	0.0145	(m)
Width of the rail A55	b_r	0.055	(m)
Height of the rail A55	h_1	0.065	(m)
Yield strength	f_y	235.0	(MPa)
	$f_{y,d}$	231.80	(MPa)

Table 3 Validation by comparison with (Pham, 2006)

	Ref. (Pham, 2006)	Matlab code	Error (%)
$\frac{d}{t_w}$	31.03	31.020	0.03
$\frac{V_{z,Sd}}{V_{z,Rd}}$	0.133	0.1329	0.08
$\frac{\max V_{y,Sd}}{V_{y,Rd}}$	0.012	0.0119	0.84
$\frac{\tau_{V,Ed}}{\frac{\left(f_y/\sqrt{3}\right)}{\gamma_M}}$	0.199	0.1989	0.05
$\frac{V_{Ed}}{0.5V_{pl,T,Rd}}$	0.290	0.2890	0.35
$\frac{N_{Sd}}{A_{FT} \cdot f_{y,d}} + \frac{M_{y,Sd}}{W_{el,y} \cdot f_{y,d}} + \frac{M_{z,Sd}}{W_{el,z} \cdot f_{y,d}}$	0.420	0.4289	2.08
$\frac{N_{sd}}{A_{TF,\mathrm{net}} \cdot f_{y,d}}$	0.004	0.0041	2.44
$\left[\frac{\gamma_{Ff} \bullet \Delta\sigma_{E2}}{\frac{\Delta\sigma_C}{\gamma_{Mf}}}\right]^3 + \left[\frac{\gamma_{Ff} \bullet \Delta\tau_{E2}}{\frac{\Delta\tau_C}{\gamma_{Mf}}}\right]^5$	0.033	0.0328	0.61

(Ellingwood et al., 1982), and the material properties are based on (Bartlett et al., 2003).

Reliability assessment results in Monte Carlo simulation with convergence criteria of 1.50(%), after performing 2520 MC simulations, the failure probability $P_f = 0.056$, as shown in Fig. 7. This result shows that all deterministic input parameters satisfy the safety condition according to the EC-3. However, the failure probability is $P_f = 0.056$ (safety probability 94.4%) This has practical implications in design practices considering the randomness of the input parameters is important.

Sensitivity analysis

In this work, the effect of input parameters on the reliability of the crane runway girder is investigated based on global Sobol sensitivity indices. The input parameters investigated included B, b, h, t, s, f_y, and $f_{y,d}$. The nominal

Table 4 Input parameters for reliability assessment

Properties	Variables	Nominal	Mean/nominal	COV	Distribution	Ref
Crane loading	Q_{c1}	60.0 (kN)	1.05	0.10	Normal	Ellingwood et al., (1982)
	Q_{c2}	10.0 (kN)	1.05	0.10	Normal	Ellingwood et al., (1982)
	$Q_{h,k}$	100.0 (kN)	1.05	0.10	Normal	Ellingwood et al., (1982)
Crane girder	L_e	15.00 (m)	1.00	–	Deterministic	
Crane girder runway	B	9.00 (m)	1.00	0.05	Normal	Ellingwood et al., (1982)
	b	0.250 (m)	1.00	0.05	Normal	Ellingwood et al., (1982)
	h	0.450 (m)	1.00	0.05	Normal	Ellingwood et al., (1982)
	t	0.028 (m)	1.00	0.05	Normal	Ellingwood et al., (1982)
	s	0.0145 (m)	1.00	0.05	Normal	Ellingwood et al., (1982)
Rail	b_r	0.055 (m)	1.00	–	Deterministic	
	h_1	0.065 (m)	1.00	–	Deterministic	
Material	f_y	235.0 (MPa)	1.10	0.06	Lognormal	Bartlett et al., (2003)
	$f_{y,d}$	231.80 (MPa)	1.10	0.06	Lognormal	Bartlett et al., (2003)

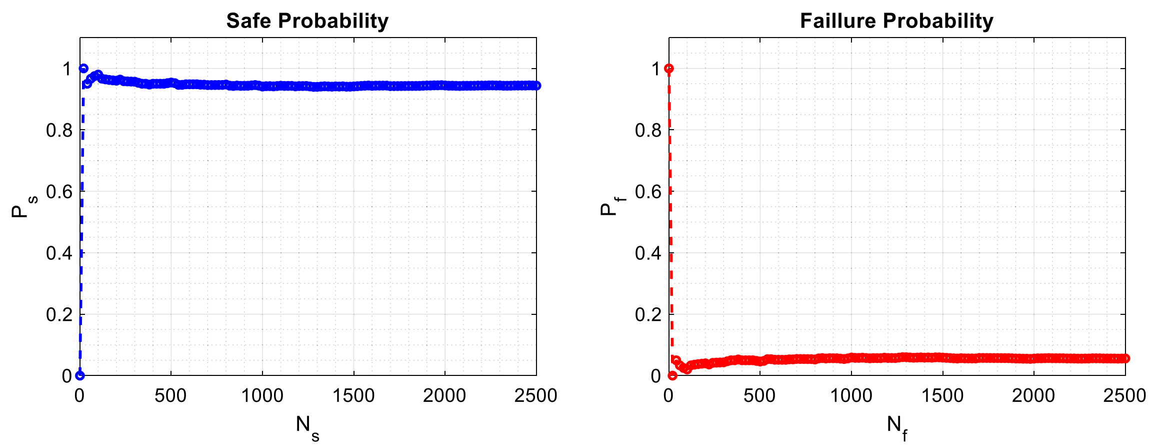

Fig. 7 Safe and failure probability in Monte Carlo simulation

Table 5 Input parameters for sensitivity analysis

Properties	Units	Symbol	Distribution	Range
Crane girder runway	m	$X_1(B)$	Uniform	8.55–9.45
	m	$X_2(b)$	Uniform	0.2375–0.2625
	m	$X_3(h)$	Uniform	0.4275–0.4725
	m	$X_4(t)$	Uniform	0.026–0.029
	m	$X_5(s)$	Uniform	0.0138–0.0152
Material	(MPa)	$X_6(f_y)$	Uniform	223.25–246.75
	(MPa)	$X_7(f_{y,d})$	Uniform	220.21–243.39

Table 6 Mean estimation of first and total sensitivity Sobol's indices with 50.000 Monte Carlo simulation

Variable	First sensitivity Sobol's indices	Total sensitivity Sobol's indices
$X_1(B)$	0.0729	0.0328
$X_2(b)$	0.0695	0.0073
$X_3(h)$	0.0695	0.0073
$X_4(t)$	0.0695	0.0073
$X_5(s)$	0.0695	0.0073
$X_6(f_y)$	0.9927	0.9271
$X_7(f_{y,d})$	0.0695	0.0073

values and distributions of those parameters are shown in Table 5.

The global Sobol sensitivity indices analysis results are shown in Table 6 and Fig. 8. It can be seen that the $X_6(f_y)$ has the largest influence (70.0%) with first-order Sobol indices and an increase (93.0%) with total Sobol indices. While the remaining parameters have reduced from 5.0 to 1.0%. The obtained results imply that the input variables have a small dependency.

Conclusions

This study presented the reliability assessment result of the crane runway girder. A design process for the crane runway girder is developed based on EC-3. Random variables for input design parameters are considered in the proposed procedure. The effect of random input parameters investigated based on global Sobol' sensitivity analysis has been also presented. Specifically, research has been achieved.

- A reliability-based design process for the crane runway girder is developed.
- The proposed reliability-based design procedure is built successfully based on the MATLAB platform, and it can be convenient for design practices.
- A numerical validation has been performed. The result shows that random variables for input design parameters considered in the proposed procedure have a safe probability $P_s = 94.40\%(P_f = 5.60\%)$.
- The effect of random input parameters investigated based on global Sobol' sensitivity analysis has been also presented. The $X_6(f_y)$ has the largest influence (70.0%) with first-order Sobol indices and an increase (93.0%) with total Sobol indices.

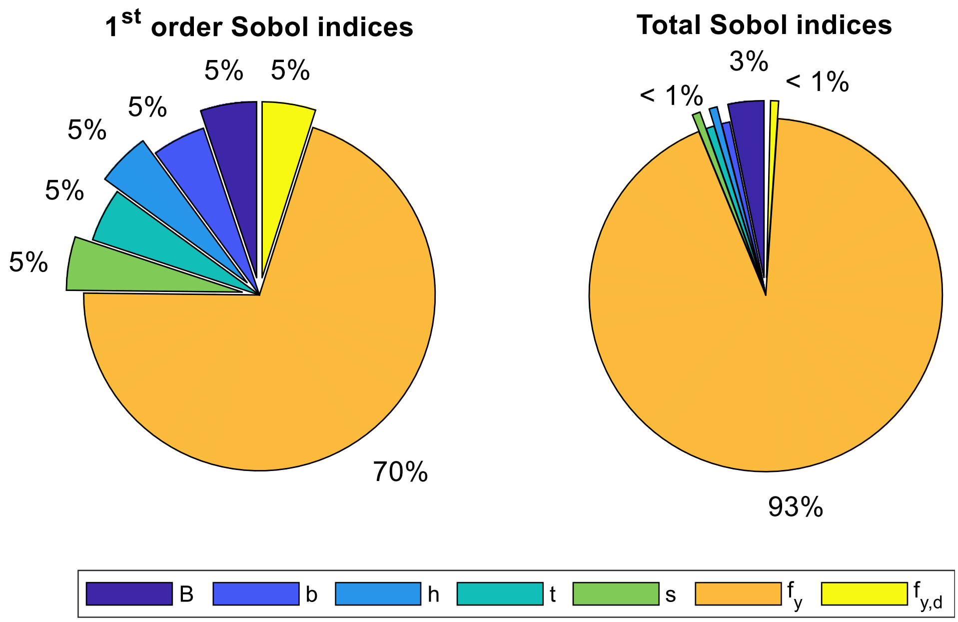

Fig. 8 Effect of input parameters on the reliability of the crane runway girder

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Data availability The data used to support the findings of this study are included in the article.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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