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Reliability-based design optimization for box-booms considering strength degradation and random total working time †

Zhonglai Wang, Gang Li, Hong-Zhong Huang*, Xiao-Ling Zhang and Yanfeng Li

School of Mechanical, Electronic, and Industrial Engineering, University of Electronic Science and Technology of China, Chengdu, Sichuan 611731, China

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Abstract

Box-booms are widely used in some cranes. The strength of box-booms would continuously deteriorate with the use of time. In this paper, gamma process is employed to describe strength degradation when dealing with the overall stability of the box-boom. Furthermore, the total working time is not deterministic but random because of the random arrivals of tasks and the random working time of every task. By accounting for strength degradation and the random total working time, a time-dependent reliability-based design optimization (RBDO) model for the box-boom is proposed. An engineering case is used to illustrate the proposed model.

Keywords: Box-boom; Strength degradation; Gamma process; Reliability-based design optimization; Total random working time

1. Introduction

Uncertainty exists widely in engineering practices, such as variation in material property, load, manufacturing and utilization [1, 2]. In traditional design, uncertainty is represented with a safety factor to ensure the quality of products. However, there are two main disadvantages for the design based on the safety factor [3]. On one hand, the selection of a safety factor is based on the experience of designers. Hence it is difficult to constitute a uniform standard. On the other hand, it is impossible to express the quantificational margin of safety for the designed product. In order to address these two disadvantages, RBDO is proposed [4, 5].

In the RBDO model, two scenarios are considered: time-independent and time-dependent. In the time-independent RBDO model, strength and stress are both considered as random variables. But time-independent RBDO model usually can not satisfy the requirements of engineering problems [6]. Therefore, strength is not a static random variable but a stochastic process in the real world. Then a time-dependent RBDO model should be constructed for the given stochastic process [7, 8]. For the box-boom of a crane, strength degradation should also be considered. However, strength degradation usually occurs when the boom is put into use but not any time of the lifetime. Therefore, the actual total working time should be studied and the current RBDO should be extended to include the actual total working time.

In this paper, we attempt to extend the time-dependent RBDO model by integrating strength degradation and actual total working time at the design stage. In the extended time-dependent RBDO model, gamma process is employed to describe the strength degradation; the actual total working time is obtained by combining random arrivals of tasks using the homogeneous Poisson process (HPP) and random working time of every task is obtained by a Weibull distribution.

The reminder of the paper is organized as follows. A brief introduction to the random total working time model is provided in Sec. 2. In Sec. 3, the extended time-dependent RBDO model of the box-boom is given. An engineering case follows in Sec. 4 to illustrate the proposed model. Conclusions are drawn in Sec. 5.

2. Random total working time model

The actual total working time is usually less than its lifetime and, furthermore, is a compound stochastic process in engineering practices. The crane is a typical example since its arrivals of tasks and working time of every task are both random.

HPP is usually used to describe arrivals of tasks:

$$P\left\{N(t)=n\right\}=\frac{(\lambda t)^k e^{-\lambda t}}{n!} \tag{1}$$

*Corresponding author. Tel.: +86 28 61830248, Fax.: +86 28 61830227
E-mail address: hzhuang@uestc.edu.cn

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where λ is the rate parameter.

Let the working time of every task W_i follow a Weibull distribution. The probability density function is

$$f_w(t) = \frac{\beta}{\alpha}(\frac{t}{\alpha})^{\beta-1}\exp\{-(\frac{t}{\alpha})^{\beta}\} \tag{2}$$

where α is the scale parameter, and β is the shape parameter.

Hence the total working time is a compound HPP and is

$$T_{total} = \sum_{i=1}^{N(t)} W_i \,. \tag{3}$$

$E(T_{total})$ and $Var(T_{total})$ could be obtained based on characteristics of the compound HPP.

$$E(T_{total}) = \lambda t \frac{1}{\alpha}\Gamma\left(1+\frac{1}{\beta}\right) \tag{4}$$

$$Var(T_{total}) = \lambda t \frac{1}{\alpha^2}\Gamma\left(1+\frac{2}{\beta}\right) \tag{5}$$

From Eqs. (4) and (5), we know that $E(T_{total})$ and $Var(T_{total})$ are functions of time t.

3. Time-dependent RBDO model of the boom

In terms of the design specifications of crane GB3811-2008, the following design constraints should be satisfied at the design stage. In the following constraints and RBDO model, $\mathbf{d},\mathbf{X}$ and $\mathbf{P}$ are the vectors of deterministic design variables, random design variables and parameters.

(1) Constraint of overall stability

$$g_1(\mathbf{d},\mathbf{X},\mathbf{P}) = \frac{N}{A} + [\frac{1}{1-\frac{N}{N_{crx}}}]\frac{M_{Hx}+M_{Ox}+M_{fx}}{W_{1x}} + [\frac{1}{1-\frac{N}{N_{cry}}}]\frac{M_{Hy}+M_{Oy}+M_{fy}}{W_{1y}} - [\sigma] \tag{6}$$

where $[\sigma]$ is the allowable stress; A is the area of cross section; W_{1x} and W_{1y} are the bending module of the standard cross-section in the direction of *x*, *y*-axis respectively; N_{crx} and N_{cry} are the critical Euler load in the direction of *x*, *y*-axis respectively; $M_{Hx} = T_x \cdot l_{1x}$ and $M_{Hy} = T_y \cdot l_{1y}$ are maximum bending moments caused by the lateral load in the luffing and rotation planes respectively; l_{1x} and l_{1y} are the length of the boom when the boom is fully stretched in the luffing plane and rotation planes; M_{Ox} and M_{Oy} are the boom-side moments, and $M_{Ox} = M_{Ly}$, $M_{Oy} = 0$; M_{fx} and M_{fy} are moments produced by the deflection of the boom gap.

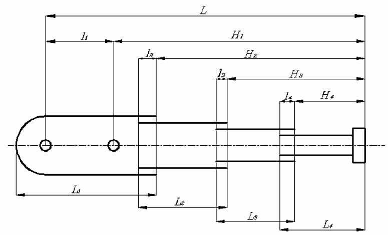

Fig. 1. Geometry dimension of the boom.

(2) Constraint of stiffness

Stiffness should be satisfied in both the luffing and rotation planes.

In the luffing plane, the constraint of stiffness is

$$g_2(\mathbf{d},\mathbf{X},\mathbf{P}) = \frac{1}{1-\frac{N}{N_{crx}}}\cdot(f_{wy} + \Delta_y \sum_{i=1}^{K-1}\frac{H_{i+1}}{l_{i+1}}) - [f_y]\,. \tag{7}$$

In the rotation plane, the constraint of stiffness is

$$g_3(\mathbf{d},\mathbf{X},\mathbf{P}) = \frac{1}{1-\frac{N}{N_{cry}}}\cdot(f_{wx} + \Delta_x \sum_{i=1}^{K-1}\frac{H_{i+1}}{l_{i+1}}) - [f_x] \tag{8}$$

where f_{wx} and f_{wy} are the boom-side deflection caused by the lateral load in the luffing and rotation planes respectively in the case of axial compression $N = 0$; Δ_x and Δ_y are the horizontal gap between the two adjacent booms in the rotation and luffing planes respectively, which are usually determined by the working conditions and manufacturing process; $[f_x] = 0.7\times10^{-3}L^2$ and $[f_y] = 10^{-3}L^2$; H_{i+1} and l_{i+1} are geometry dimensions, as shown in Fig. 1.

(3) Constraints of strength of non-overlapping parts

$$g_4(\mathbf{d},\mathbf{X},\mathbf{P}) = \frac{N}{A_z} + [\frac{1}{1-\frac{N}{0.9N_{crx}}}]\frac{M_{zy}}{W_{zy}} + [\frac{1}{1-\frac{N}{N_{cry}}}]\frac{M_{zx}}{W_{zx}} - [\sigma] \tag{9}$$

where A_z is the area at the cross section *Z*; $M_{zy} = M_{Ly} + T_x(L-z)$ and $M_{zx} = T_y(L-z)$ are the bending moments caused by the lateral load in the luffing and rotation planes, respectively; *L* is the whole length of boom; W_{zy} and W_{zx} are the flexural module in the direction of the *y* and *x*-axis respectively.

In order to guarantee the strength at each cross section, the strengths of a few of the dangerous cross sections at the non-

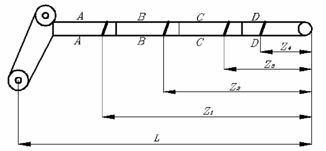

Fig. 2. Positions of probabilistic constraints.

overlapping part are selected as the probabilistic constraints. According to the force analysis, the dangerous cross sections lie in the joints of the jibs and the crossing point between the main jib and the oil cylinder. The detailed positions are provided in Fig. 2.

The volume is treated as the objective function to be minimized. The strength degradation would affect the overall stability. Therefore, the constraint of overall stability is a time-dependent probabilistic constraint. Other constraints related to stiffness and strength of non-overlapping parts are time-independent probabilistic constraints. Then the time-dependent RBDO model could be provided as follows:

$$\min \quad f(\mathbf{d},\mathbf{X},\mathbf{P})$$

$$\text{s.t.} \quad \Pr\{g_1(\mathbf{d},\mathbf{X},\mathbf{P};t) = \frac{N}{A_1} + [\frac{1}{1-\frac{N}{N_{crx}}}]\frac{M_{Hx}+M_{Ox}+M_{fx}}{W_{1x}} + [\frac{1}{1-\frac{N}{N_{cry}}}]\frac{M_{Hy}+M_{Oy}+M_{fy}}{W_{1y}} - D(T_{total}) - [\sigma] \le 0\} \ge [R_1]$$

$$\Pr\{g_i(\mathbf{d},\mathbf{X},\mathbf{P}) \le 0\} \ge [R_i] (i = 2,...,7)$$

where $[R_i]$ $(i = 2,...,7)$ are reliability targets.

Gamma process is employed to represent the strength degradation of the box-boom in this paper [9, 10]. Since T_{total} is a stochastic process and also a parameter of gamma process, $D(T_{total})$ is a compound stochastic process. Therefore, different optimal designs can be obtained at the different given confidence levels.

4. An engineering case

The lifting weight of the boom is Q_0 = 55 kN when the main boom is fully stretched and the margin is R = 7 m. This is the most dangerous condition of the boom. The boom is made up of HG60 with the allowable stress $[\delta] = 317$ MPa. The lifting impact factor $\varphi_1 = 1.1$; the dynamic load factor in the lifting process $\varphi_2 = 1.1$; yaw $\phi = 4$. The information on random design variables and parameters is given in Table 1.

For the arrivals of tasks, the parameter of HPP is $\lambda = 0.084/\text{hour}$. For the working time of every task, the parameters of a Weibull distribution are $\alpha = 9$ and $\beta = 5$. Parameters of the gamma process are $v(t) = 12.96t$ and $u = 4\times10^4/\text{MPa}$.

The probabilistic constraints on the strength of non-overlapping parts at the most dangerous cross sections A-A, B-B, C-C and D-D are treated as reliability constraints. The bending module in the luffing and rotation planes at the four cross sections are provided in Table 2.

Table 1. Information on random design variables and parameters.

		Mean	Std	Distribution
Random design variables	D	--	5×10^{-5} m	Normal
	H	--	5×10^{-5} m	Normal
	K	--	5×10^{-5} m	Normal
Random parameters	N	92750 N	9275 N	Normal
	T_X	14750 N	1475 N	Normal
	T_Y	4385 N	438.5 N	Normal
	M_{Ly}	21350 N	2135 N	Normal
	H_2	22.666 m	5×10^{-5} m	Normal
	H_3	15.146 m	5×10^{-5} m	Normal
	H_4	7.62 m	5×10^{-5} m	Normal
	L	32.45 m	5×10^{-5} m	Normal
	l_2	2.136 m	5×10^{-5} m	Normal
	l_3	1.786 m	5×10^{-5} m	Normal
	l_4	1.55 m	5×10^{-5} m	Normal
	l_{1x}	26.44 m	5×10^{-5} m	Normal
	l_{1y}	26.44 m	5×10^{-5} m	Normal
	Z_1	24.83 m	5×10^{-5} m	Normal
	Z_2	17.304 m	5×10^{-5} m	Normal
	Z_3	9.784 m	5×10^{-5} m	Normal
	Z_4	6.01 m	5×10^{-5} m	Normal

Table 2. Bending module for the four cross sections.

	In the luffing plane (mm^3)	In the rotation plane (mm^3)
A-A	1.07×10^6	8.82×10^5
B-B	1.58×10^6	1.48×10^6
C-C	2.35×10^6	2.24×10^6
D-D	2.83×10^6	2.73×10^6

Table 3. Optimal design results at the lifetime.

Design variables	D (m)	H (m)	L (m)	f(mm^2)
Optimal design	0.0615	0.4337	0.0559	0.0269

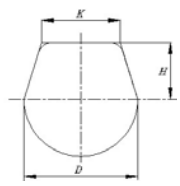

Fig. 3. Oval cross section of the boom.

The oval cross section of the boom is shown in Fig. 3.

Since the length is a constant, the area of the cross section is treated as the objective function.

In the traditional RBDO, the lifetime of the boom is usually considered as the total working time. The optimal design results are provided in Table 3 at the given lifetime 40000 hours.

Table 4. Optimal design results at the mean value.

Design variables	D (m)	H (m)	L (m)	f (mm^2)
Optimal design	0.0144	0.7032	0.0131	0.0097

Table 5. Optimal design results at $\mu + 3\sigma$.

Design variables	D (m)	H (m)	L (m)	f (mm^2)
Optimal design	0.0154	0.6862	0.0140	0.0102

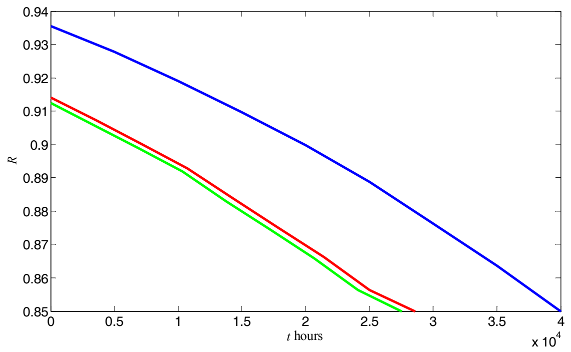

Fig. 4. Time-dependent reliability curves for the three cases.

Herein, two cases are considered for the engineering cases: at the mean value and $\mu + 3\sigma$ of the random total working time.

The optimal design results at the mean value of the random total working time are given in Table 4.

The optimal design results at $\mu + 3\sigma$ of the random total working time are given in Table 5.

From Tables 3-5, it is known that the area at the lifetime 0.0269 is much greater than that at the mean value 0.0097 and at $\mu + 3\sigma$ 0.0102. Furthermore, the optimal designs are different for their different optimal design variables.

The corresponding time-dependent reliability curves for the abovementioned three cases are given in Fig. 4.

In Fig. 4, the blue line denotes the time-dependent reliability when the lifetime is treated as the total working time; the red line denotes the time-dependent reliability when the mean value of the random total working time is used; and the green line denotes the time-dependent reliability when the value at $\mu + 3\sigma$ of the random total working time is used. From Fig. 4, it is known that the initial reliabilities (when $t = 0$) are also different for the three cases. Therefore, it is necessary to account for the actual total working time at the design stage with consistence of engineering problems.

5. Conclusions

This work is preliminary research to extend the time-dependent RBDO by accounting for strength degradation and random total working time for the boom of a crane. In this work, the extended time-dependent RBDO model is built by accounting for strength degradation with a gamma process, random arrivals of tasks with via HPP and random working time of every task based on a Weibull distribution. The optimal design results show the difference between considering the random total working time and without consideration. The model that considers the random total working time will be more suitable for engineering problems. Furthermore, the proposed model will be applicable for equipment that works spasmodically.

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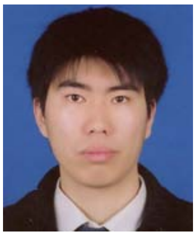

Zhonglai Wang is currently an associate professor of the School of Mechanical, Electronic, and Industrial Engineering at the University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731. His research interests include reliability-based design optimization, robust design and life-cycle reliability-based design.

Hong-Zhong Huang is a full professor and the Dean of the School of Mechanical, Electronic, and Industrial Engineering, University of Electronic Science and Technology of China. He received his Ph.D in Reliability Engineering from Shanghai Jiaotong University, China. He has published 150 journal papers and 5 books in the field of reliability engineering. He has held visiting appointments at several universities in the USA, Canada, and Asia. He received the Golomski Award from the Institute of Industrial Engineers in 2006. His current research interests include system reliability analysis, warranty, maintenance planning and optimization, computational intelligence in product design.