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# Probabilistic approach for the fatigue design of tower cranes

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## Résumé :

*Les acteurs du bâtiment veulent maximiser l'efficacité de leurs équipes et matériels dans le but de minimiser la durée des chantiers. Cela conduit à une utilisation intensive des grues dont la charpente est principalement composée d'éléments mécano-soudés. De ce fait, les Ingénieurs Structure doivent considérer la résistance à la fatigue durant le dimensionnement. L'objectif de ce travail est de démontrer l'utilité d'une méthode fiabiliste pour une meilleure optimisation du dimensionnement à la fatigue d'éléments de flèche de grues à tour.*

## Abstract :

*Crane owners want to maximize the efficiency of their equipment and teams in order to minimize the amount of time needed to complete a construction site. This leads to very intensive crane use and stress on crane structures made primarily of welded steel elements (plates and beams). Therefore, Structural Engineers have to consider fatigue resistance during the design process. The aim of the paper is to demonstrate the utility of a probabilistic approach for a better optimization of the fatigue design of tower cranes elements (e.g. jib elements).*

**Mots clefs : reliability ; fatigue ; tower cranes**

## 1 Introduction

Tower crane structures are made of steel plates or beams connected by welding and, due to intensive workload, fatigue resistance is an important aspect to consider for Structural Engineers. Classical design methods can lead to non-optimized structures with non-uniform safety margins, and consequently to a non-optimized distribution of safety factors related to fatigue. The proposed work takes place further to two projects called DEFFI [1] and APPRoFi [2] in which reliability approaches for fatigue assessment of industrial applications were experimented and developed. Based on these previous works, the aim here is to quantify and optimize the safety margins with respect to fatigue of tower crane steel structures, by means of probabilistic approaches.

This study focuses on jib elements of a top slewing tower crane. The jib's function is to support the trolley that moves the load from one radius to another (see  $R_1$  and  $R_2$  in figure 1). This jib structure is submitted to load variation depending on the radius and the live hoisted load.

All structures made by metal plates or beams connected by welding are subjected to fatigue phenomenon after many years of intensive cyclic use. This phenomenon is showing large variation for several reasons. First, there is the randomness of the loading on the structure, due to the variability of crane use by the owners. Second, the non-even fabrication process (manual welding) leads to material and geometry differences in the structure. Third, the great variety of geometries makes it impossible for

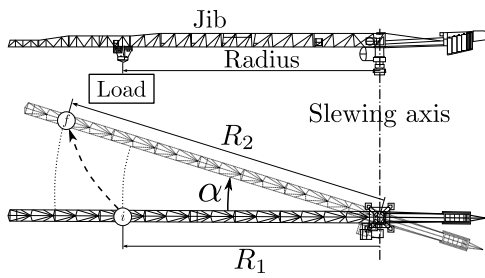


FIGURE 1 – Crane vocabulary definitions.

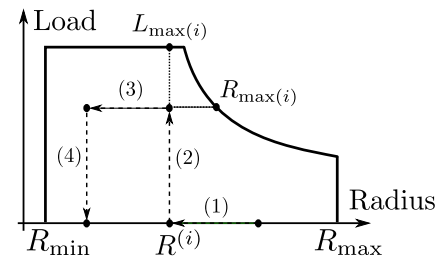


FIGURE 2 – Load chart definition

life prediction to reach the same predictability in every single case. Fourth, complex structural modeling requires simplification hypothesis that may result in variations depending on analysis techniques utilized.

European Standards for fatigue design of tower cranes [3] consider deterministic loading cycles regardless of time in service, that lead to non-optimized safety margins. The aim of this work is to assess the fatigue damage probability of a crane structural member, namely the jib element, depending of the time in service. This kind of approach requires data collection concerning the real use of the crane. These data are used to model random variables having an influence on the fatigue damage of the structure.

## 2 Stochastic modeling of crane use

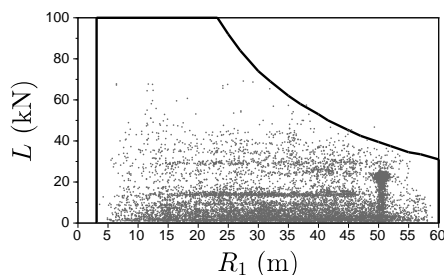
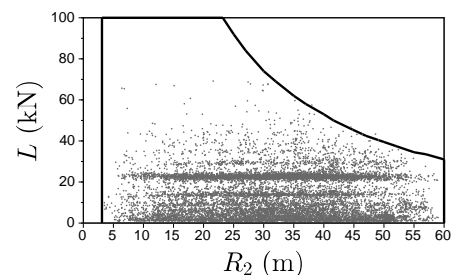
### 2.1 Definitions

To understand how tower cranes work, it is necessary to introduce the concept of load chart. The example of load chart depicted in figure 2 shows the maximum load it is possible to lift according to the position of the trolley along the jib, i.e. the radius  $R$ . For a given value of radius  $R^{(i)}$  at time  $t$ , the load  $L^{(i)}$  that can be lifted by the crane is necessarily below the load chart, i.e. below  $L_{\max}^{(i)}$ .

Another important thing to consider is the motion sequence of a loading cycle which consists of four phases (see figure 2) : (1) trolley in movement without load, (2) lifting of the load, (3) trolley in movement with the load lifted, (4) drop off of the load.

### 2.2 Load and Radius time histories

A recording has been performed during five months on a crane working on a construction site. Figures 3 and 4 present the recorded data versus the load chart respectively at the beginning and at the end of crane cycles. On the latters, horizontal tendencies can be observed at different levels of load. It corresponds to different natures of hoisted loads which can be identified separately. Three types of work were distinguished on the jobsite. The first one corresponds to the concrete pouring cycles where the concrete bucket is moved from the concrete batching plant to the wall or the floor to be fabricated. The second one corresponds to the positioning cycles. The loads lifted then are forms, walkways or prefabs. Finally, all the cycles that do not match the previous definitions are brought together in the category "other cycles".

FIGURE 3 – Data versus load chart ( $R_1$ ).FIGURE 4 – Data versus load chart ( $R_2$ ).

Figures 5a, 5b and 5c present the radii histograms respectively at the beginning and at the end of the crane cycles. Figure 5a shows that all concrete pouring cycles start at a radius of 50 meters. That corresponds to the position of the concrete batching plant on the studied construction site. All the other figures associated to the radii present quite similar profiles. The mode is more or less situated around the mean radius of the jib.

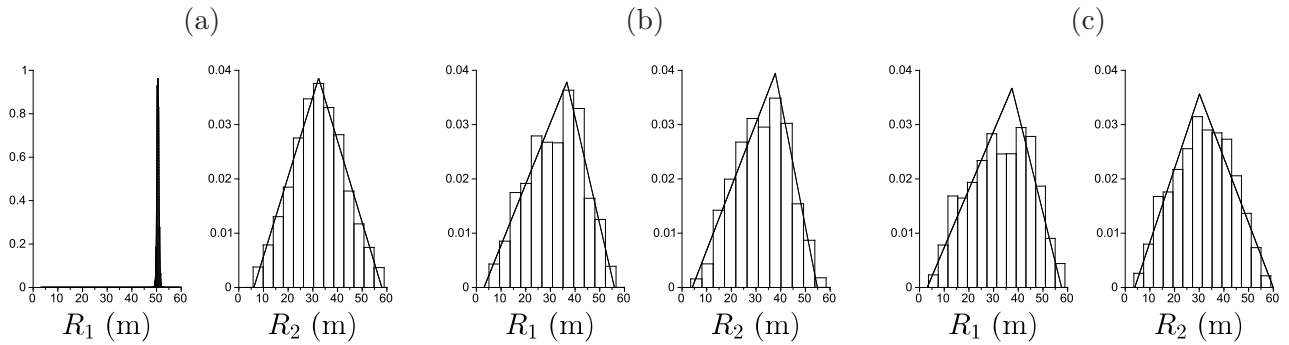


FIGURE 5 –  $R_1$  and  $R_2$  histograms for (a) concrete pouring cycles, (b) positioning cycles and (c) other cycles.

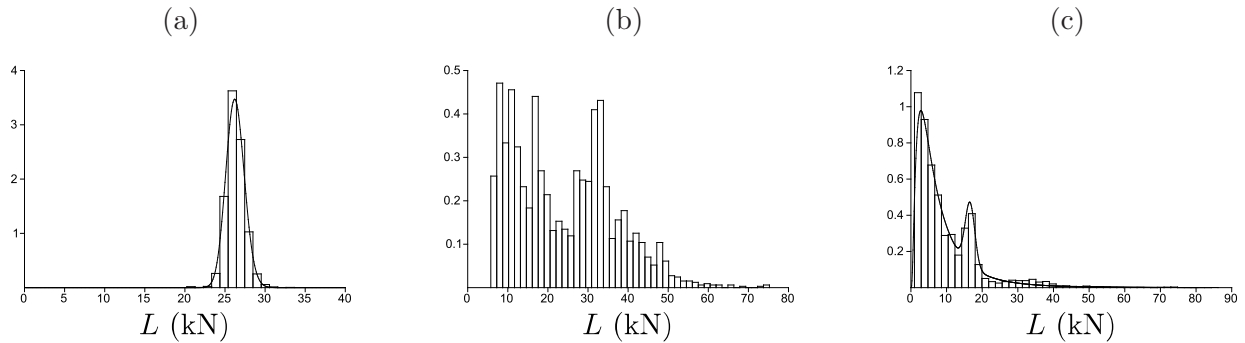


FIGURE 6 – Histogram of the maximum load lifted for (a) concrete pouring cycles, (b) positioning cycles and (c) other cycles.

$R_1$		Estimation	Choice	
①	$\mathcal{N}$	$\mu$	$0.84R_{max}$	$\mathcal{U}(R_{min}, R_{max})$
		$\sigma$	0.4 m	0.5 m
②	$\mathcal{T}$	$a$	$R_{min}$	$\mathcal{U}(1, 2)R_{min}$
		$b$	$0.93R_{max}$	$\mathcal{U}(0.9, 1)R_{max}$
		$c$	$1.16R_m$	$\mathcal{U}(0.7, 1.3)R_m$
③	$\mathcal{T}$	$a$	$R_{min}$	$\mathcal{U}(1, 2)R_{min}$
		$b$	$0.96R_{max}$	$\mathcal{U}(0.9, 1)R_{max}$
		$c$	$0.82R_m$	$\mathcal{U}(0.7, 1.3)R_m$

① Concrete pouring ② Positioning ③ Other

TABLE 1 – Parameters for the fitted distributions for  $R_1$ .

$R_2$		Estimation	Choice	
①	$\mathcal{T}$	$a$	$1.97R_{min}$	$\mathcal{U}(1, 2)R_{min}$
		$b$	$0.97R_{max}$	$\mathcal{U}(0.9, 1)R_{max}$
		$c$	$1.025R_m$	$\mathcal{U}(0.7, 1.3)R_m$
②	$\mathcal{T}$	$a$	$1.35R_{min}$	$\mathcal{U}(1, 2)R_{min}$
		$b$	$0.91R_{max}$	$\mathcal{U}(0.9, 1)R_{max}$
		$c$	$1.2R_m$	$\mathcal{U}(0.7, 1.3)R_m$
③	$\mathcal{T}$	$a$	$1.25R_{min}$	$\mathcal{U}(1, 2)R_{min}$
		$b$	$R_{max}$	$\mathcal{U}(0.9, 1)R_{max}$
		$c$	$0.95R_m$	$\mathcal{U}(0.7, 1.3)R_m$

① Concrete pouring ② Positioning ③ Other

TABLE 2 – Parameters for the fitted distributions for  $R_2$ .

Figures 6a, 6b and 6c depict the maximum hoisted load histograms. Figure 6a depicts the histogram of the maximum load recorded during the concrete pouring cycles. The mean of the distribution is around 26 kN and corresponds to the load of the concrete bucket with the dynamic overload.

Concerning the positioning cycles, the distribution of maximum load lifted is much more widespread. It can be explained by the fact that there are a lot of possible combinations of forms, walkways and prefabs. Most of the time, there are three standardized sizes of form on a construction site (2.5 m, 1.25 m and 0.625 m). An equipped form of 2.5 m width weighs 17 kN, dynamic overload included. It could explain the peaks situated approximately at 34 kN, 17 kN and 8.5 kN (see figure 6b). The rest of the variability is probably due to the lifting of walkways or prefabs (balconies, stairs, etc.). Figure 6c shows the distribution of the load lifted during the other cycles where two main modes can be identified. The peak around 17 kN seems to correspond to the displacement of form ballasts. The rest of the variability of the distribution comes from the lifting of iron frameworks, junk buckets, etc.

$L$		Estimation	Choice
①	$\mathcal{N}$	$\mu$	26.3 kN
		$\sigma$	$0.05\mu$
②	-	Modes : 8.5, 17 and 34 kN	Randomly chosen in table 5 <sup>°</sup>
③	$f_X(x)$	$\alpha$	0.88
		$\mu_1$	8.8 kN
		$\sigma_1$	9.5 kN
		$\mu_2$	16.6 kN
		$\sigma_2$	1.3 kN

① Concrete pouring ② Positioning ③ Other

<sup>°</sup> For  $R = R^{(i)}$ ,  $L \leq L_{\max}^{(i)}$  (see figure 2)

\* Radius-dependent :  $\mu \leq L_{R_{\max}}$

•  $f_X(x) = \alpha\mathcal{N}(\mu_1, \sigma_1) + (1 - \alpha)\mathcal{LN}(\mu_2, \sigma_2)$

TABLE 3 – Parameters for the fitted distributions for  $L$ .

## 2.3 Load and radius random variables

The assessment of jib element use for each construction site can be made through the modeling of a set of random variables. The choice of parametric radius and load distributions is derived from the studied jobsite, considered as representative. The implicit hypothesis here is to consider that the randomness of the construction sites can be modeled by varying the parameters of the distributions.

Concerning the radii modeling, a normal distribution was chosen to model  $R_1$  for concrete pouring cycles (see figure 5a). The mean of the distribution is defined by the location of the concrete batching plant and the standard deviation is fixed by expert opinion. All the other distributions associated to the radii of the cycles are modeled thanks to triangular distributions (see figures 5a, 5b and 5c). Thus, for each triangular distribution, it is necessary to define three parameters (two bounds and one mode).

Concerning the modeling of the load, for the concrete pouring cycles it was chosen to define a normal variable with a mean equal to the weight of the filled concrete bucket plus a dynamic overload. The possible concrete buckets that can be randomly chosen are given in table 4. Regarding positioning cycles, figure 6b shows that it is not possible to define a simple model for the lifted load. Instead, it was considered that no more than 5 linear meters of forms can be lifted in one time. Then, knowing that for a given radius of the trolley, the load chart constrains the maximum possible lifted load (see figure 2), a configuration of forms is randomly chosen between the possible ones at each cycle. Table 5 gives the weight of all the possible form configurations and their associated probability. Note that a difference is made in term of probability between configurations 1, 2, 4, and 7 and the others. The implicit assumption is made that it is more probable to hoist these four configurations than the others. Concerning the other cycles, it was chosen to consider a linear combination of lognormal and normal distributions to model the other lifted loads (see figure 6c). The mean of the normal distribution corresponds to the load of a ballast. The mean and the standard deviation of the lognormal distribution are randomly chosen for each construction site.

All the estimated parameters and the assumptions made on these parameters are summarized in tables 1, 2 and 3 where  $\mathcal{U}$ ,  $\mathcal{T}$ ,  $\mathcal{N}$  and  $\mathcal{LN}$  are respectively the uniform, triangular, normal and lognormal probability laws.

Capacity (L)	800	1000	1250	1500	2000
Weight (kN)	24	25	37	43	57

TABLE 4 – Possible concrete buckets.

N°	1	2	3	4	5	6	7
Weig.	$w/4$	$w/2$	$3w/4$	$w$	$5w/4$	$3w/2$	$2w$
Prob.	$p/4$	$p/4$	$q/3$	$p/4$	$q/3$	$q/3$	$p/4$

$w = 15$  kN,  $p = 0.7$  and  $q = 1 - p$

TABLE 5 – Possible form configurations.

## 2.4 Equivalent number of cycles per year

Once the loading history of the jib element is established based on the previous probability laws, an equivalent number of cycle, at the reference load range  $\Delta F_{ref}$  (see figure 7), must be determined.  $\Delta F_{ref}$  is the reference load range used for the determination of the number of cycles of resistance  $N_{res}$ .

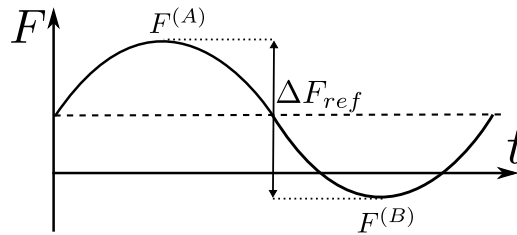


FIGURE 7 – Illustration of the reference load cases.

$N_{eq_{use}}$  is calculated based on the Miner linear damage accumulation rule  $N_{eq_{use}} = \sum_i (\Delta F_{(i)} / \Delta F_{ref})^c$ .  $\Delta F_{(i)}$  is the load range of cycle  $(i)$  and  $c$  is the fatigue strength exponent related to structural fatigue resistance.

## 3 Calculation of fatigue damage probability

### 3.1 Monte Carlo Simulations

MC simulations are performed in order to assess the distribution of  $N_{eq_{use}}(x, t)$  where  $x$  is the vector of all random variables and  $t$  is the time in years. The steps are explained below :

For each crane simulation (i.e. for each MC iteration) :

1. Random sampling of a number of construction sites with their duration ( $\mathcal{U}(4, 24)$  months) and with the time between two construction sites ( $\mathcal{U}(0.5, 2)$  months).
2. For each construction site :
  - (a) Transformation of the construction site duration into a number of cycles assuming that : the median number of working days per month is equal to 22, the median number of crane cycle per hour is equal to 12, the number of working hours per day is randomly chosen in the normal distribution  $\mathcal{N}(9, 1.5)$  hours.
  - (b) The number of cycles per type of work for the construction site is then inferred taking into account the following rates : 33% for concrete pouring cycles, 17% for positioning cycles, 50% for other cycles.
  - (c) Random sampling of jib length for the construction site according to the possible configurations from 25 m to 65 m.
  - (d) Random sampling of the parameters associated to  $R_1$ ,  $R_2$  and  $L$ .
  - (e) Generation of the corresponding time-histories.
  - (f) Cycle counting.
  - (g) Calculation of an equivalent number of cycles after  $t$  years.
3. Registering of  $N_{eq_{use}}(x, t)$ .

### 3.2 Modeling of the equivalent number of cycles per year

Time-histories of 40 years have been generated 5000 times following the method presented above. The distributions of  $N_{eq_{use}}(x, t)$  found after 10, 20, 30 and 40 years are depicted in figure 8. A lognormal model is used to fit the empirical distributions.

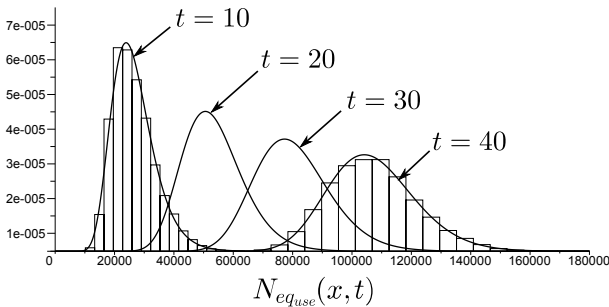


FIGURE 8 –  $N_{eq_{use}}(x, t)$  after 10, 20, 30 and 40 years.

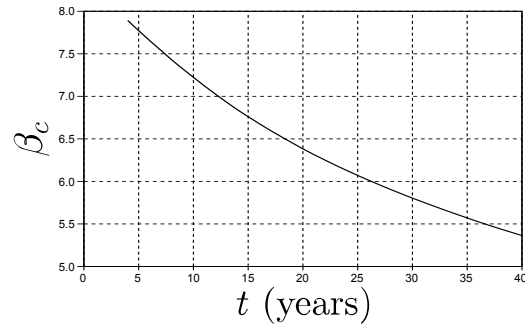


FIGURE 9 – Reliability index of the jib element versus the time.

### 3.3 Reliability index calculation

To calculate the fatigue damage risk of the jib element, it is necessary to define a performance function taking into account the fatigue resistance on one hand, and the crane use on the other hand. Although the obtention of the number of cycle of resistance  $N_{res}$  is not detailed in this paper, note that a lognormal law is chosen to model it. Due to the lognormal nature of the resistance and use distributions, the performance function and the reliability index can be expressed as follows :

$$G(x, t) = \ln N_{res} - \ln N_{eq_{use}}(x, t) \Rightarrow \beta_c(t) = \frac{\lambda_{N_{res}} - \lambda_{N_{eq_{use}}}(t)}{\sqrt{\xi_{N_{res}}^2 + \xi_{N_{eq_{use}}}(t)^2}} \quad (1)$$

where  $\lambda_X$  and  $\xi_X$  represent respectively the mean and the standard deviation of  $\ln(X)$ . Figure 9 depicts the reliability index versus the time in years. Note that the reliability index of the jib element is high regardless the number of years of work of the crane (more than 5 even after 40 years), compared to the target  $\beta$  values proposed by recommendations such as [4].

## 4 Conclusions

In this work, a probabilistic approach has been developed to model tower cranes use and the reliability of jib elements was assessed. For 40 years of lifetime, the reliability index of these elements was found to be higher than 5, which is large compared to recommendations.

Two main perspectives were identified concerning crane use modeling. It is planned to include more data records coming from other jobsites, on one hand, and to develop a model allowing transformation of any jobsite drawing into crane loading time-histories, on the other hand. Relatively large statistics of crane use could be produced in limited time thanks to this technique.

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