# Wind effects on out-of-service tower cranes

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ABSTRACT: *Recent storms events in Europe gave evidence of the strong wind sensitivity of the tower cranes. The behaviour of these structures in strong winds was then studied on a reduced scale model in a boundary layer wind tunnel in order to characterize aerodynamic effects induced by the surrounding built environment. The model of tower crane proposed consists on a rigid mast and a rotating jib which movement is defined as a single degree of freedom: the rotation relative to vertical axis. The overturning risk is evaluated thanks to the quantification of the bending moment at the base of the tower crane. This data is a function of the jib nose angular position and can be split up into four contributions: inertial, centrifugal, gravity and obviously aerodynamic moment. A parametric study on the position of the tower crane relative to various built environments was carried out to extract the most unfavourable erection configurations.*

## 1 INTRODUCTION

The recent windstorms in Europe showed the sensitivity of tower cranes to wind effects. Since the violent storm in 1999 in France, CSTB has developed a new research axis to study the overturning risks and to characterize wind actions on these structures. As far as material and human risks are engaged, crane constructors try to improve as much as possible the aerodynamic properties and limit wind loads of their products.

In out-of-service situation, tower cranes are free to turn around the vertical axis: the motor is disconnected. Without surrounding buildings, the jib tends to align with the mean direction of the wind in a safety position, counter weights backwards so upwind. Standard procedures of dimensioning are used to estimate wind actions for an isolated tower crane in an optimized safety configuration. However, such a method ignores wind disturbances produced by the surrounding environment. Local variation in wind speed and direction can lead to the rotation of the jib nose until a transversal position, unexpected and dangerous. This phenomenon is scarce and occurs in specific built configurations. Tower crane behaviour is then controlled by interactions between the wind and the surrounding buildings. As a consequence, the fluctuating loads and especially peak values of aerodynamic bending moment are complex to estimate by a computed approach. CSTB experimental skills lead to design a reduced scale dynamic model, studied in a wind tunnel ([1], [2]).

The designed model satisfies geometrical and kinematical similarities. Therefore it reproduces a realistic behaviour of an out-of-service tower crane with a rotating part governed by a one degree of freedom differential equation of motion.

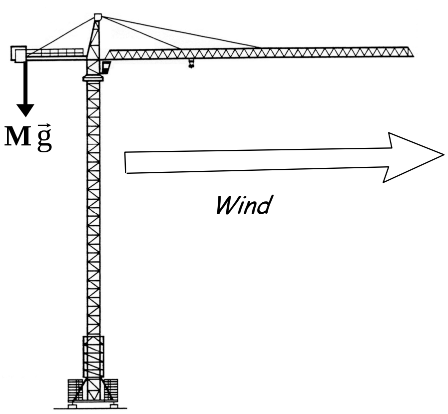
After a design period, instrumentation and then validation, this efficient model enables to detect and estimate the built environment effects. The analysis achieved during the last few years, enables a classification of predominant site effects.

## 2 TOWER CRANE IN TURBULENT FLOW, THE BUILT ENVIRONMENT ROLE

### *2.1 Wind actions on an isolated crane*

During windstorms, the rotating part is free to rotate. Its natural tendancy is to stay in the wind mean direction and to follow the low frequencies fluctuations. Due to its high inertia and size, the crane is not influenced by the high frequencies perturbations.

*Figure 1 An out-of-service crane without surrounding buildings*




Without surrounding environnment, the crane is in tail wind condition. The jib fluctuates and the counter weights of the jib equilibrate the aerodynamic loads.

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*2.2 Wind actions on a crane in a built environment*

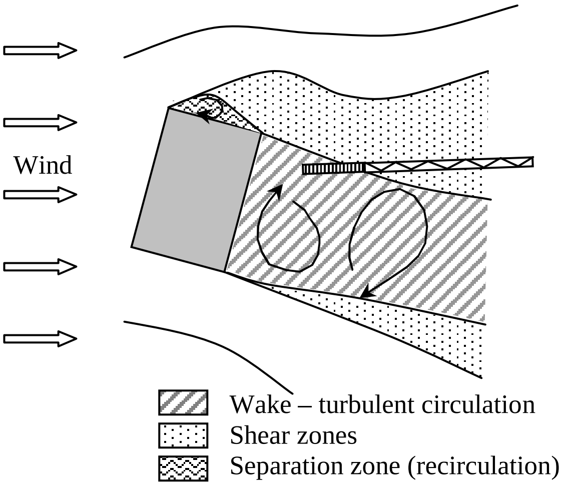



*Figure 2 An out-of-service crane behind a building*

The presence of the building modifies the flow properties around the crane which can be then in various disrupted layers of circulation (Fig 2). These areas depend on the building sizes and turbulent scales of the oncoming wind. The instability properties of each zone can be noted. The wake zone can be characterized by low wind velocities and strong direction fluctuations induced by the vortices. In the shear layers, wind speed and in the same way aerodynamic loads increase.

So, the position of the crane relative to the building will determine the encountered wind fields, the rotating part can be located in zones of various natures. Then, the crane can leave its stability position and turn till a transversal new one or even keep on turning if equilibrium isn't found. These behaviours are strongly dependent of the respective dimensions of the crane and the built environment. For example, if the jib of the crane is significantly higher than the building (Fig 3), or if the rotating part is definitely longer than transversal dimension of the building (fig 4), the crane won't be significantly disturbed.

*Figure 3 Tower crane third higher than the building*

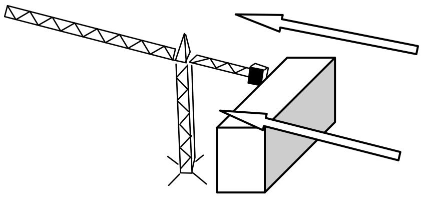
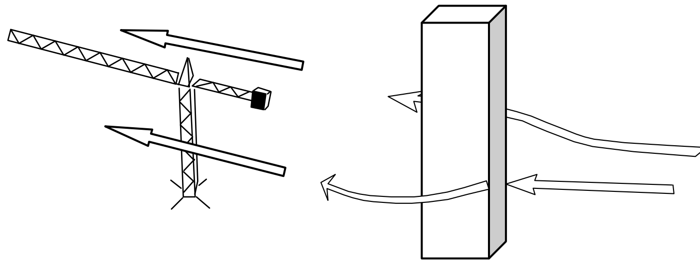
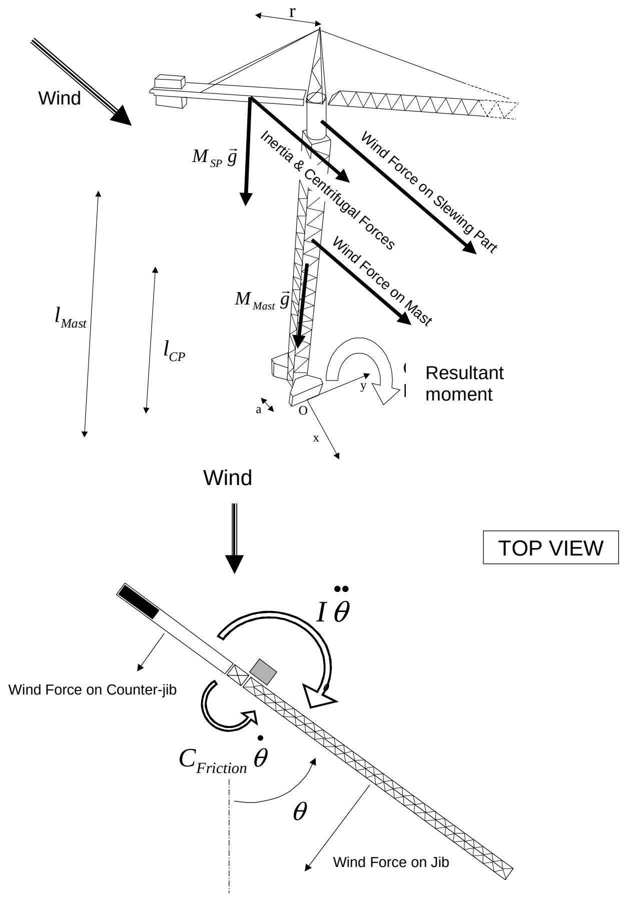


*Figure 4 Rotating part longer than transversal dimension of the building*



# 3 MATHEMATICAL MODEL

*Figure 5 Moments and forces schema*




A mathematical approach was proposed by D. Voisin in his doctoral thesis [1], 2003. The jib motion is described with a single degree of freedom, the angular position $\theta$. The mast and the rotating part are supposed to be rigid bodies, their deformation are neglected. Resultant moment at crane base level can be resolved into its components, expressed as functions of $\theta$. Four major contributions are considered: inertial and centrifugal rotating part moments, gravity moment and fluctuating wind moment. The resultant moment is then expressed as

$$\overrightarrow{M_{resultant}(O)}.\vec{y} = \overbrace{-\ddot{\theta}\, m_{RP}\, l_{Mast}\, r\sin\theta}^{\text{Inertial}} \overbrace{-\, \dot{\theta}^{2}\, m_{RP}\, l_{Mast}\, r\cos\theta}^{\text{Centrifugal}}$$
$$\overbrace{-\,a\, m_{Mast}\, g - [r\cos\theta + a]\, m_{RP}\, g}^{\text{Gravity}}$$
$$\overbrace{+\,l_{CP} Fx_{Wind\to Mast} + l_{Mast} Fx_{Wind\to RP}}^{\text{Wind}} \qquad (1)$$

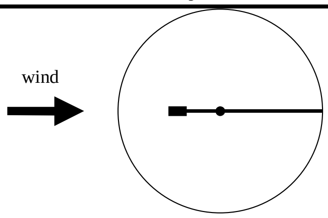
where $\overrightarrow{M_{resultant}(O)}.\vec{y}$ is the resultant moment at crane base level at tipping point O, $\vec{y}$ the unit vector transversal to the wind direction, $m_{RP}$ the mass of the rotating part, $m_{Mast}$ the mass of the mast, $l_{Mast}$ the height of mast, $l_{CP}$ the height of the mast aerodynamic center, r the rotating part barycentre to crane vertical axis length, a the cross shaped-base spacing, g the gravity acceleration, $Fx_{Wind\to Mast}$ the drag component of wind force on mast and $Fx_{Wind\to RP}$ the drag component of wind force on rotating part.

Resultant moment is mainly governed by aerodynamic forces and gravity moment resulting essentially from weights in the counter jib. Inertial and centrifugal rotating part moments are second order terms. Weights set the crane in a steady condition when they balance the carried loads during service or the aerodynamic load during violent wind. Nevertheless, the structure stability is reduced when tail wind condition is left.

Following the angular position $\theta = 0$, contributions can be either restoring or overturning moments.

Tail wind position is the steadier condition. Only aerodynamic terms are overturning moments and are minimized due to the low area exposed to wind.

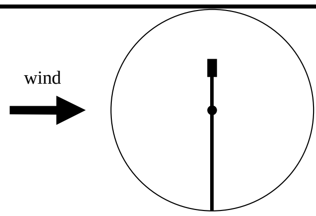
Tail wind $\theta = 0$, jib nose downwind




$$\overrightarrow{M_{resultant}(O)}.\vec{y} = -\dot{\theta}^{2}\, m_{RP}\, l_{Mast}\, r$$
$$-\,a\,(m_{Mast} + m_{RP})\, g - r\, m_{RP}\, g$$
$$+\,l_{CP} Fx_{Wind\to Mast} + l_{Mast} Fx_{Wind\to RP} \qquad (2)$$

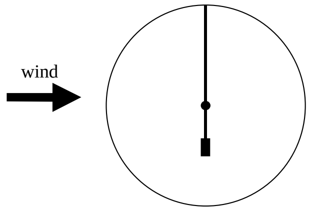
The transversal position is a critical situation. Aerodynamic loads are maximal whereas the gravity moment resulting from counter-jib weights is nil.

$\theta = \dfrac{\pi}{2}$




$$\overrightarrow{M_{resultant}(O)}.\vec{y} = +\ddot{\theta}\, m_{RP}\, l_{Mast}$$
$$-\,a\,(m_{Mast} + m_{RP})\, g$$
$$+\,l_{CP} Fx_{Wind\to Mast} + l_{Mast} Fx_{Wind\to RP} \qquad (3)$$

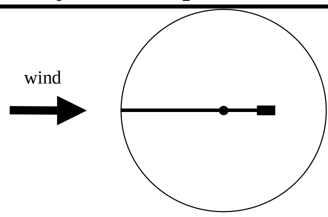
$\theta = -\dfrac{\pi}{2}$




$$\overrightarrow{M_{resultant}(O)}.\vec{y} = -\ddot{\theta}\, m_{RP}\, l_{Mast}$$
$$-\,a\,(m_{Mast} + m_{RP})\, g$$
$$+\,l_{CP} Fx_{Wind\to Mast} + l_{Mast} Fx_{Wind\to RP} \qquad (4)$$

In both transversal conditions, the sign of inertia moment depends on the sign of acceleration $\ddot{\theta}$.

$\theta = \pi$, jib nose upwind




$$\overrightarrow{M_{resultant}(O)}.\vec{y} = \dot{\theta}^{2}\, m_{RP}\, l_{Mast}\, r$$
$$-\,a\,(m_{Mast} + m_{RP})\, g - r\, m_{RP}\, g$$
$$+\,l_{CP} Fx_{Wind\to Mast} + l_{Mast} Fx_{Wind\to RP} \qquad (5)$$

This last position is also a critical situation. Only the term $-a\,(m_{Mast} + m_{RP})\, g$ is a restoring moment.

## 4 EXPERIMENTAL TOOLS

### *4.1 Wind tunnel facility description*

The tests are conducted in a CSTB boundary layer which cross-section is 2.3m high x 4 m wide. The simulation is adjusted using roughness on the floor. The wind tunnel velocity range is of 0-10 m/s.

### 4.2 *Scale model of crane*

According to space requirements to reproduce built environment and the dimensions of cross-section, a 1/80 geometric scale $\lambda_L$ has been chosen. The crane prototype has to satisfy at the same time geometric, cinematic and dynamic similarities conditions.

The geometric similarity is adjusted to a Potain MD238 crane with a possibility to represent with three jig lengths similar to 30, 45m and 65m long.

The cinematic similarity imposes to check that the ratio of the structure acceleration to the fluid acceleration is the same for both prototype and model. Actually, this condition is equivalent to respect the equality of Strouhal numbers for both systems and has been confirmed using wind tunnel tests.

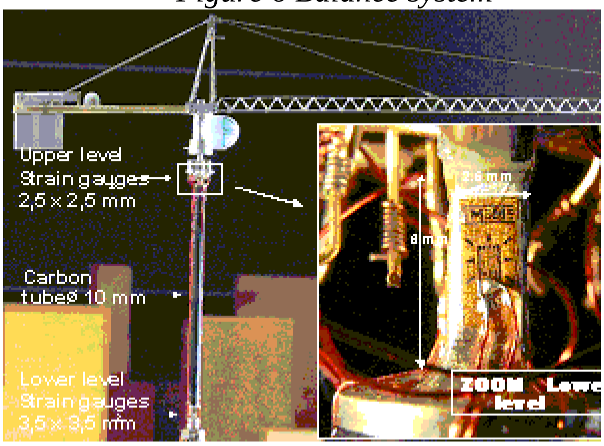
The dynamic similarity exists if the ratio of each force is the same between model and prototype. Therefore, mass and inertia distributions, friction coefficient have to result from similarity rules. Indeed the gravity moments imply to respect the Froude number similarity. As a consequence the wind speed scale is defined as the square root of geometric scale. According to similarity laws, mass inertia, friction coefficients and loads of real model are written as functions of prototype properties by the relations below:

$$\begin{aligned} m_{real} &= \lambda_L m_p \\ I_{real} &= \lambda_L^5 I_p \\ C_{friction})_{real} &= \lambda_L^4 \sqrt{\lambda_L}\, C_{friction})_p \\ Moment_{real} &= \lambda_L^4 Moment_p \end{aligned} \qquad (6)$$

So, the prototype represents a 1/80 scale crane and the respect of similarity laws enables to reproduce cinematic and dynamic behaviour.

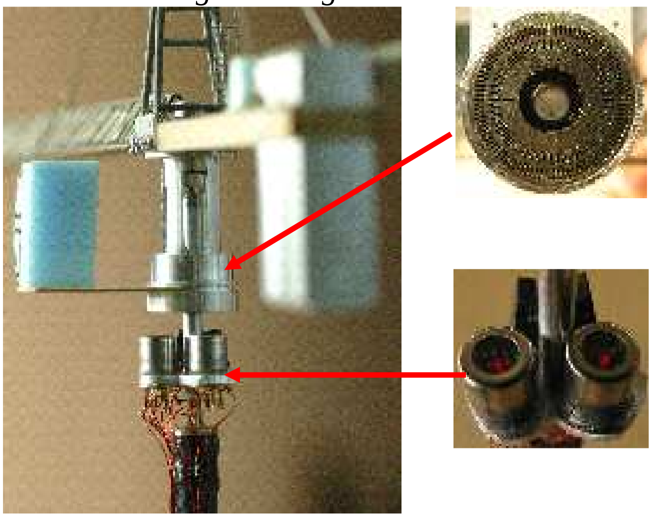
A balance with two levels of strain gauges measures acting loads and enables to access to resultant moment at the base of the crane.

*Figure 6 Balance system*




The two stages are connected by a 10mm diameter carbon tube that simulates the drag properties of the mast. The junction between the mast and the rotating part is adjusted using a central pin to reduce friction coefficient.

*Figure 7 Angular encoder*



An angular encoder composed by three optoelectronics sensors and a reflecting surface provides the instantaneous angular position of the jib.

### 4.2 *Experimental process*

Measurements are performed in 1 minute similar to nearly 9 minutes in reality, at a sampling frequency of 200 Hz. At initial position, the jib has a tail wind configuration and is free to turn around its vertical axis. The wind sets up from a nil speed to the mean wind speed desired. To analyse environment impact, a first test is performed without any surrounding building and then measurements are compared to a configuration with the actual surrounding buildings for various wind directions. Using angular position given by the encoder, the gravity effects are well known and if centrifugal and inertia effects are neglected, it is easy to determine the aerodynamic loading.

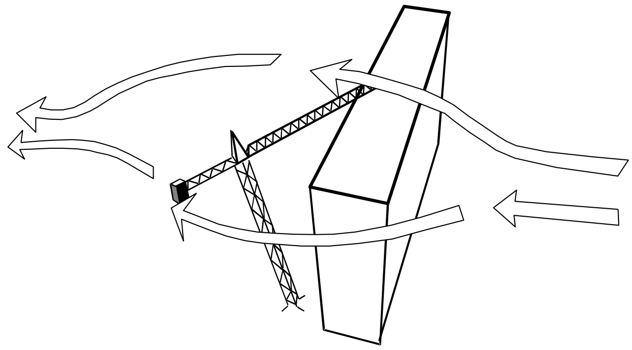
## 5 CLASSIFICATION OF ENVIRONMENT EFFECTS

Since 1999, CSTB experiments configurations of building sites in wind tunnel and detects few scarce cases of interactions between cranes and their surrounding built environment. As a consequence, a classification in families of the most common environment effects stands out. This analysis can be evident when the crane is close to a single building. To simplify the surroundings can be divided in two classes: high-rise buildings and large buildings, similar to social housing erected in France in the seventies. Nevertheless, when several buildings interfere, it becomes more difficult to clarify.

*5.1 Corner effects*

The corner effects are observed in presence of large buildings. When the wind meets such an obstacle, the major part of the flow passes over. The remaining part circumvents by a lateral path. Then, the risky implantation of the crane is near the corner of the building when it has the same order of height. In such a situation, auto-rotating phenomenon is possible but the most common behaviour is a motion towards a transversal position parallel to a side of the construction.

*Figure 8 Corner effect*

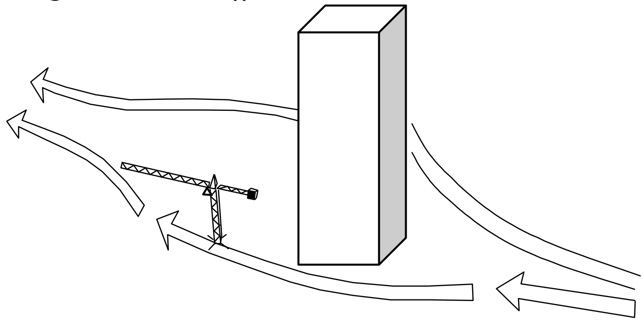


*5.2 Wake effects*

Around high-rise buildings, the flow progresses through a lateral path. If the dimensions of the obstacle are significant, the flow is perturbed on a large area where the crane can be set. In general the height of the jib is mostly smaller than the construction. Two configurations can be distinguished: downstream and upstream cranes

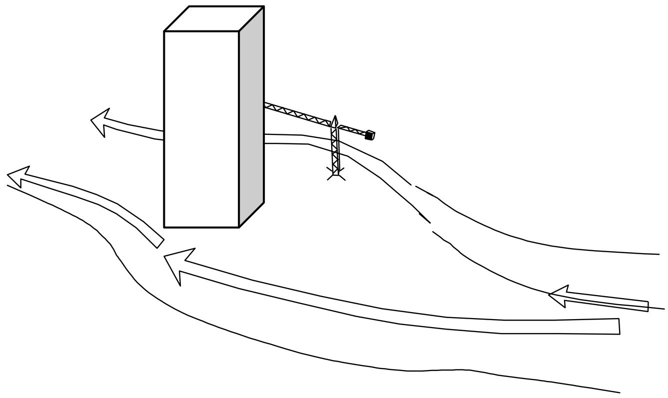
In a configuration with a downstream crane, the rotating part can be at the time in a wake zone and an accelerated area. If a rotating motion is initiated, the jib inertia is significant enough to make a half-turn. Then the same phenomenon can repeat. The dangerous situation results when the jib comes in a transversal position relative to an accelerated flow inducing overloading on the structure.

*Figure 9 Wake effect: downstream crane*



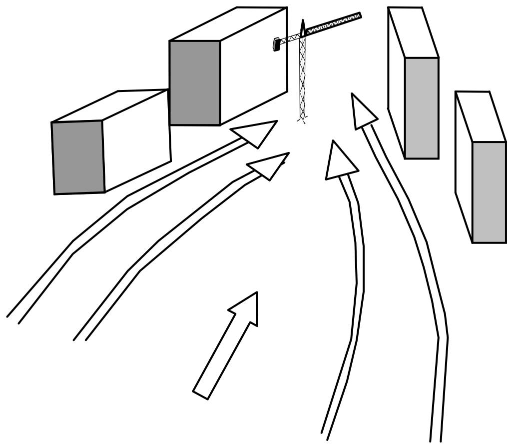
An upstream crane can be sucked in the lateral flow turning around the building. Then, it takes a transversal position. Nevertheless the aerodynamic loads stay smaller than those measured for a downstream crane.

*Figure 10 Wake effect: upstream crane*



*5.3 Local acceleration effects*

*Figure 11 Local acceleration effects*

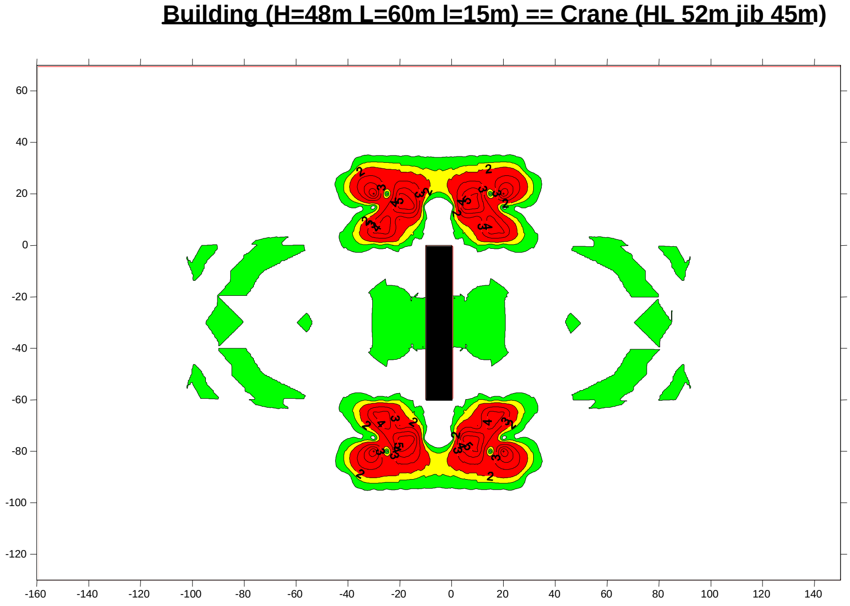


The local acceleration effects are more difficult to describe and to schematize. Indeed, several buildings interfere and there is not a simple schema to summarize all the configurations. The built environment creates a corridor where the wind is guided and accelerated in restricted areas. In general, the jib don't move and stay in a stable position but the aerodynamic loads increase. A typical example is the "Venturi" effect.

## 6 PARAMETRIC STUDY

Next years, this research will intend to characterize each one of these relevant environment effects in order to elaborate rules and recommendations for actors of building industry. This work has been initiated in 2004 and will continue in 2005-2006. A parametric study has been scheduled in collaboration with INRS to detect the characteristic and relative dimensions of cranes and buildings responsible for such phenomena. As a first step, mappings will be established for a specific crane (jib length, jib height) and a built environment. They will show critical crane location in the building site. Then a synthesis will be conducted to detect interaction rules.

*Figure 12 Example of mapping*




The Figure 12 shows an example of mapping. The crane was situated near a 48m high, 60m long and 15m large building. The jib height was fixed to 52m and the jib length to 45m. The critical locations are indicated in red. In this configuration, the environment effect is similar to a corner effect described in 5.1. The parametric study is in progress.

## 7 CONCLUSIONS

An experimental process has been established to study environment effects on tower cranes in wind tunnel boundary layer. A 1/80 scale model reproduces the crane dynamic behaviour in an out-of-service condition. An instrumentation of the model enables to access to aerodynamic moment and to the instantaneous angular position of the jib.

This model crane is an efficient tool to study surrounding built environment effects on cranes. According to CSTB skills and building sites tested in wind tunnel, a classification of the most frequently observed phenomena has been established. The study will continue to identify significant crane and building characteristics that produce the phenomenon apparition. The goals of this study are the establishment of rules and recommendations for building industry actors to secure the construction sites.

## 8 ACKNOWLEDGEMENT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