Analysis of accidents with tower cranes on construction sites and recommendations for their prevention

K Radlov* and G Ivanov

Department „Construction Technology and Mechanization“, Faculty of Structural Engineering, University of Architecture, Civil Engineering and Geodesy; 1046 Sofia, Bulgaria

*E-mail: kradlov@abv.bg

Abstract. Analyzing and investigating accidents with tower cranes on construction sites is a particularly important preventative measure to ensure their accident-free work and reduce the number of occupational accidents at the construction site. The urgency of this problem is increasing very much in view of the relatively long operational life of the tower cranes on construction sites. This article presents various types of results from researches related to the analysis of accidents with tower cranes on construction sites worldwide. In addition, an approach for analysis of the absolute probability of a major tower crane accident caused by failures of mechanical components is considered, as well as analysis of possible sequences of failures of mechanical components leading to a tower crane accident, which are analyzed based on Fault Tree Analysis (FTA). An adequate statistical approach is proposed to establish the most significant organizational and technical causes, mainly related to the organization of the construction site and the activities for maintenance of the machine park, which cause accidents with tower cranes. An approach is proposed to calculate the conditional probability (weighting factor) of a specific organizational and technical cause to lead to a serious accident with the tower crane using Bayesian formulas, as well as an approach to determine the total assessment for each organizational and technical cause regarding its potential for causing accidents. Finally, proposals and recommendations are made related to the identification of key technical and organizational measures, the adequate and timely implementation of which could lead to a reduction in the number of occupational accidents with tower cranes on construction sites.

1. Introduction

In construction practice, incidents related to accidents during the operation of tower cranes are not uncommon. Such events not only have the potential to cause great damage to private property and forcible interruption of construction activities, but can also lead to accidents involving injuries to people. Much effort is being made by scientists, researchers and organizations worldwide, which are aimed at conducting a detailed analysis of accidents with tower cranes on construction sites ([1], [2], [3], [4] and others). The report [2] examines accidents with different types of construction cranes, which analyzes their potential to cause major accidents involving serious injuries to people. The results of this research testify to the serious consequences of accidents with construction cranes. The study [3] analyzes the calendar age of tower cranes in which accidents occurred in the period from 1983 to 2014, emphasizing that the average age of tower cranes involved in accidents is 16.9 years, most accidents occurred with tower cranes aged about 14 years, and a large proportion (21.6%) of accidents occurred with tower cranes over 25 years old. The main goal of all researches is to identify adequate recommendations that will lead to timely prevention and/or reduction of the number of accidents and occupational accidents with tower cranes.
2. Review of the results of previously performed statistical analyzes regarding the actual causes of accidents with tower cranes worldwide

The Health and Safety Laboratory (HSL) has carried out an analysis of worldwide tower crane accidents from 1989 to 2009 [4], in an attempt to establish the causes of each accident. The research report [4] includes only accidents that occurred in the most widely used in construction top-slewing tower cranes, which are from different manufacturers (Liebherr, Potain, Wolff, Favelle Favco, Comedil, Jaso Peiner, Kroll, Raimondi, Kodiak and others). A total of 85 major accidents with these cranes were analyzed (leading to: fall of the entire crane, collapse of the boom, etc.), which were conditionally divided into 7 different categories, depending on the causes for their occurrence:

- accidents occurred during installation, dismantling or extension of the crane tower/boom - 29 accidents (34% of the total number). These are accidents that occur during lifting, turning or assembly/disassembly of large and heavy components of the tower crane structure. The technologies and procedures for assembly/disassembly and extension of the boom/tower of the tower crane in most cases require the implementation of a complex sequence of steps that are associated with the performance of work at height. These complex activities are usually associated with a long duration of operations and require a large number of staff, which creates additional preconditions for human error, leading to severe consequences;

- accidents occurred as a result of external natural influences - 15 accidents (18% of the total). Of these accidents, 2 were caused by earthquakes, and the remaining 13 were due to strong winds. Some of the accidents caused by strong winds are related to the omission to provide the free rotation of the crane boom during the wind load, as well as to the incorrect position of the boom (angle of inclination) in the tower cranes with luffing boom;

- accidents caused by improper use of the crane (mistake made by the operator and/or riggers) - 6 accidents (7% of the total). They are mainly related to: lifting stuck loads, overloading the crane, impact/interaction between two cranes on the same construction site, etc. Possible prerequisites that create conditions for the occurrence of such accidents are: insufficient qualification of the crane operator and/or the riggers, poor quality of the construction supervision on the site, etc. ;

- accidents occurred as a result of compromising mechanical/structural components of the tower crane - 4 accidents (5% of the total number). They are mainly related to: broken bolts of the support-rotating device; broken weld in bearing structural component; damage/destruction of an element of the kinematic chain of a lifting mechanism and/or a jib crane mechanism; failure of the brake system in one of the mechanisms of the crane, etc. Possible prerequisites that create conditions for the occurrence of such accidents are mainly the following: omission to perform the mandatory periodic checks/inspections of the mechanical components of the crane; poor quality checks/inspections of mechanical components; poor quality repair works on mechanical components of the crane, etc. ;

- accidents occurred as a result of compromising the foundation/supporting structure under the crane - 2 accidents (2% of the total number). They are caused mainly by non-compliance with the manufacturer's instructions during the construction of the supporting structure and the foundation under the tower crane (the so-called "original design");

- accidents caused by compromising electrical components or the crane control and management system - 1 number of accidents (1% of the total number). They are mainly related to a fault in the inverter/controller (PLC) settings of the crane drive system, which in some cases could lead to uncontrolled discharge of the load. The risk of such damage and accidents is greater with modern cranes, which are equipped with more complex control systems. This largely depends on the competencies of the electrician who performs the settings of the control system during the installation of the crane or replacement of spare parts for the electrical equipment of the crane during operation;
• accidents for which the cause is still unidentified (unknown) - 28 accidents (33% of the total number). These are accidents whose causes cannot be defined with sufficient reliability because the available information about them is not sufficiently accurate and/or sufficiently detailed.

![Figure 1](image)

**Figure 1.** Results obtained for the causes of major accidents with tower cranes for the period 1989-2009 according to the research report [4].

3. **Analysis of the absolute probability of a major accident with the tower crane due to failure of mechanical components**

Based on the results of research [5] it can be concluded that among the various possible mechanical damages to the tower crane, those that lead to compromise/fall of the tower crane boom are those that cause the most severe accidents on the construction site. Analysis of the absolute probability of severe accidents with the tower crane caused by failure of mechanical components is considered in the study [6]. In this study, sequences of failures of mechanical components of the tower crane are analyzed using the Fault Tree Analysis (FTA) method. Accidental failures of the individual mechanical components in the machine are distributed mainly by exponential law [7], [8]. The calculation of the risk of an accident with the tower crane $Q(T)$ is performed according to the dependence:

$$Q(T) = 1 - P(T),$$  \hspace{1cm} (1)

where:

- $T$ is the period of operating time of the tower crane, for which the probability of accident-free operation is assessed;
- $P(T)$ is the probability of accident-free operation of the tower crane for a period of operating time $T$.

$$P(T) = \exp\left[- \int_0^T E(t) \, dt \right],$$  \hspace{1cm} (2)

where $E(t)$ is the intensity of failures, which is equal to the probability that the accident will occur after a period of accident-free operation $t$. 
In assessing the absolute probability of a tower crane accident caused by failure of mechanical components, the correct definition of the causal links between individual random events (failures of individual components) plays an important role, whose individual probability of occurrence is of different frequency, but they all contribute to and lead to one final event - the occurrence of a major accident. A “Fault Tree” is built for each individual operating state of the crane. Figure 2 shows the “Fault Tree” for operating state $z_2$ - tower crane in operating state with a load suspended on the hook, in which the tower crane moves and the boom rotates simultaneously [6].

Figure 2. Tower crane “Fault Tree” in operating state $z_2$ [6].

Logical operators (AND and OR) and event symbols are used to construct the “Fault Tree”. Assuming that the selected initial random events (failures of individual components) are independent of each other, then the probability of occurrence of the final event due to several initial random events that are associated with a logical operator "AND" is determined by the following formula:

$$Q(T) = Q(E_1 \cap E_2 \cap E_3 \cap \ldots \ldots E_n) = Q(E_1, T) \cdot Q(E_2, T) \cdot Q(E_3, T) \ldots \ldots Q(E_n, T),$$

where $n$ is the number of initial random events that participate in the respective “Fault Tree”.

The probability of occurrence of the final event as a result of several initial random events that are related to a logical operator "OR" is determined by the following formula:

$$Q(T) = Q(E_1 \cup E_2 \cup E_3 \cup \ldots \ldots E_n) = 1 - Q(\bar{E}_1) \cdot Q(\bar{E}_2) \cdot Q(\bar{E}_3) \ldots \ldots Q(\bar{E}_n) =$$

$$= 1 - [1 - Q(E_1)] \cdot [1 - Q(E_2)] \ldots \ldots [1 - Q(E_n)].$$
From the diagram of figure 2 can be calculated the absolute probability of a major accident with the tower crane (falling of the entire crane or dropping the load from the hook) due to failure of a mechanical component in operating state $z_2$ (tower crane in operating state with a load suspended on the hook, during which the tower crane moves and the boom rotates simultaneously) for operating time of the crane in this operating state with a duration $-T = 8 \text{ hours}$ [6]:

$$Q_{z2}(T) = 1 - \exp(-E_{12}^{\left(4\right)}T) \bullet \exp(-E_{13}^{\left(4\right)}T) \bullet \exp(-E_{17}^{\left(4\right)}T) \bullet \exp(-E_3^{\left(4\right)}T) \bullet \exp(-E_5^{\left(6\right)}T) \bullet \exp(-E_1^{\left(5\right)}T) \bullet \exp(-E_2^{\left(6\right)}T) \bullet \exp(-E_1^{\left(1\right)}T) \bullet \exp(-E_{14}^{\left(4\right)}T) \bullet \exp(-E_8^{\left(4\right)}T) \bullet \exp(-E_9^{\left(4\right)}T) \bullet \exp(-E_3^{\left(4\right)}T) \bullet \exp(-E_4^{\left(4\right)}T) \bullet \exp(-E_5^{\left(6\right)}T) \bullet \exp(-E_6^{\left(6\right)}T) \bullet \exp(-E_8^{\left(4\right)}T) \bullet \exp(-E_6^{\left(4\right)}T) \bullet \exp(-E_8^{\left(4\right)}T) \bullet \exp(-E_4^{\left(4\right)}T) \bullet \exp(-E_6^{\left(4\right)}T) \bullet \exp(-E_8^{\left(4\right)}T) \bullet \exp(-E_3^{\left(4\right)}T) \bullet \exp(-E_5^{\left(6\right)}T) \bullet \exp(-E_8^{\left(4\right)}T) \bullet \exp(-E_6^{\left(4\right)}T) \bullet \exp(-E_8^{\left(4\right)}T)$$

$$Q_{z2}(T) = 1 - 0.91751 = 0.08249.$$  \hspace{1cm} (6)

In a similar way, “Fault Trees” can be constructed for other different possible operating states of the tower crane, and based on them to calculate the absolute probability of a major accident due to failure of a mechanical component in the respective operating state. The main purpose of these analyzes should be to look for possible weaknesses in the structure, components and/or kinematic chains of the mechanical drives of the tower cranes.

4. **Statistical approach for calculating a total assessment for each organizational and technical cause in relation to its potential for causing a tower crane accident**

When assessing the technical and organizational causes of accidents with tower cranes, there is a conditional division of accidents with tower cranes into two main groups: major accidents with tower cranes (risk of serious damage to private property and injury to a large number of people) and general accidents with tower crane (without danger of causing serious damage and injury to a large number of people).

4.1. **Assessment of the conditional probability of a specific organizational and technical cause to lead to a major accident with the tower crane**

The assessment of the probability (risk), the assumption of a specific technical or organizational cause (so-called “causative agents”) to lead to a major accident with the tower crane is the most important information related to the further identification of preventive measures and recommendations to reduce the risks of work with the tower crane and increase the safety of the construction site. The assessment of each technical or organizational cause related to the crane and its equipment according to this criterion is determined by the following dependence:

$$E_{Si} = W_{Si} \cdot P_{Si},$$

where:

$W_S$ is a weighting factor indicating the importance of the criteria being assessed. Due to the great importance of preventing a major accident with the tower crane (with the danger of causing serious damage and injury to a large number of people) for this criterion is conditionally assumed weighting factor: $W_S = 6$.
$P_{Si}$ is a coefficient of the assessment of the conditional probability of a specific technical or organizational cause (with number $i$) to lead to the occurrence of a major accident with the tower crane. This assessment varies in range $P_{Si} = (0 \div 1)$ and is determined on the basis of accumulated real statistical data (figure 1) and by using the formulas of the law of total probability and the Bayes' rule [9].

$$P_{Si} = P(S / R_i) = \frac{P(R_i / S) \times P(S)}{P(R_i)} = (0 \div 1),$$  \tag{8}

where:

$S$ is used to indicate the event of a major tower crane accident (with the danger of causing serious damage and injury to a large number of people);

$R_i$ – the technical or organizational cause with a number $i$;

$m$ – the total number of technical and organizational causes that are considered to be the “causative agents” of tower crane accidents;

$P(R_i)$ – the probability that an accident that has already occurred with the tower crane (regardless of the size of its consequences) is due to the specific technical or organizational cause $R_i$;

$P(S) = \sum_{i=1}^{m} (P(S / R_i) \times P(R_i))$ - represents the full probability of a major accident with the tower crane (with the danger of causing serious damage and injury to a large number of people), provided that an event "accident" has already occurred;

$P(R_i / S)$ – conditional probability, indicating the probability that in the event of a major accident with the tower crane (with a risk of serious damage and injury to a large number of people) this is due to a specific technical or organizational cause $R_i$. This probability can be determined using the statistical data of figure 1. For example:

- the conditional probability of a major accident with the tower crane due to errors during assembly, disassembly or extension of the tower/boom of the crane is: $P(R_1 / S) = 29/85 = 0,34$;
- the conditional probability of a major accident with the tower crane due to external natural influences is: $P(R_2 / S) = 15/85 = 0,18$;
- the conditional probability of a major accident with the tower crane due to improper use of the crane (crane operator or rigger error) is: $P(R_3 / S) = 6/85 = 0,07$;
- the conditional probability of a major accident with the tower crane due to compromise of mechanical/structural components of the tower crane is: $P(R_4 / S) = 4/85 = 0,05$;
- the conditional probability of a major accident with the tower crane due to compromise of the foundation/supporting structure under the crane is: $P(R_5 / S) = 2/85 = 0,02$;
- the conditional probability of a major accident with the tower crane due to compromise of electrical components or the crane control system is: $P(R_6 / S) = 1/85 = 0,01$;
- the conditional probability that the main cause of a major tower crane accident will eventually remain unidentified with sufficient accuracy is: $P(R_7 / S) = 28/85 = 0,33$. 
4.2. Assessment of the conditional probability of a specific organizational and technical cause to lead to a general accident with the tower crane

Assessing the probability/degree of danger/risk, if a specific technical or organizational cause/error/omission (with number \(i\)) is allowed, this will lead to a general accident with the tower crane (without danger of major damage and injury to a large number of people) is performed according to the following dependence:

\[
E_{Li} = W_L \times P_{Li},
\]

where:

- \(W_L\) is a weighting factor indicating the importance of the criterion being assessed. Due to the lesser importance of the current criterion "general accident" (compared to "major accident"), for this criterion is conditionally assumed weighting factor: \(W_L = 3\);
- \(P_{Li}\) is a coefficient of assessment of the conditional probability of a specific technical or organizational cause (with number \(i\)), to lead to a general accident with the tower crane (without danger of major damage and injury to a large number of people). This assessment varies in the range \(P_{Li} = (0 \div 1)\) and is determined in a similar way to that described in item 4.1 above.

4.3. Determination of a total assessment for each organizational and technical cause in relation to its potential for causing accidents

For each individual technical and organizational cause with number \(i\), a total assessment \(E_{0i}\) is calculated in relation to its total potential (risk) for causing any type of accidents (major and general accidents):

\[
E_{0i} = E_{Si} + E_{Li}.
\]

After the calculation of the total assessment \(E_{0i}\) in question for each of the individual organizational and technical causes ("causative agents") for the occurrence of a tower crane accident, the so-called "ranking" of the causes according to the total assessments obtained. Those organizational and technical causes ("causative agents") that have received the highest total assessments are precisely those that are key in terms of ensuring safety when working with tower cranes on the construction site.

5. Conclusion and recommendations

A statistical approach is proposed for calculating the conditional probability (weighting factor) of a specific organizational and technical cause for a serious tower crane accident, as well as an approach for determining a total assessment for each organizational and technical cause in terms of its potential for causing a tower crane accident. The most important recommendations related to ensuring the safe operation of tower cranes on construction sites are the following:

- on the basis of the calculated conditional probability on the basis of real statistical data and the obtained total assessment for each separate organizational and technical cause with regard to its potential for causing accidents, the most important organizational and technical causes ("causative agents") for accidents with tower cranes, which are key from a safety point of view, should be identified. It is to them that the main part of the subsequent organizational and technical measures for increasing the safety of work with tower cranes on the construction site should be directed as a priority after that. Of course, eliminating all possible organizational and technical causes of tower crane accidents is the most ideal option that manufacturers, service personnel and construction managers should strive for, but in practice this is very difficult to do due to the extremely large number of influencing factors;
it is recommended to perform detailed analyzes of the absolute probability of a major accident with the tower crane due to failures of mechanical components using the Fault Tree Analysis (FTA) for different possible operating states of the tower crane. Their main goal should be to look for possible weaknesses in the construction, components and kinematic chains of the mechanical drives of the tower cranes, to which the subsequent measures to improve the system for maintenance and repair of the tower crane should be directed as a priority;

it is recommended to work continuously to increase the requirements and control over the qualification of the crane operator and riggers of the tower crane, as well as to increase the requirements and control regarding the quality of maintenance and repair of the tower cranes and periodic inspections/checks on the condition of the tower cranes;

with regard to the age of the tower cranes used on construction sites, the following is recommended: 1. It is recommended that tower cranes over the age of 10 years undergo a thorough inspection before each installation; 2. Tower cranes over 20 years of age are recommended to be operated only after receiving an official confirmation from the manufacturer, by which he explicitly guarantees/confirm that their safe operation is possible for a longer period of time; 3. Tower cranes over 30 years of age are recommended to be subject to expert assessment of the technical condition or to take the necessary measures for their decommissioning. In Bulgaria, suspension of operation of cranes can in principle be done by written order of the inspectors from the General Directorate "Inspection for State Technical Supervision", when it is considered that the facility is not suitable for further safe operation, regardless of the age of the crane [10].

References
[1] Arslan M H and Kaltakci M Y 2008 Analysis of a Tower Crane Accident The Open Construction and Building Technology Journal Vol 2 pp 287-293
[2] MacCann M 2010 Understanding Crane Accident Failures: A report on causes of deaths in crane-related accidents Crane & Rigging Conference (Houston, Texas)
[3] Wiethorn J D, Gardiner M R, Bond A E, Cox E P and King R A 2015 Tower crane life expectancy. An examination of recent trends to establish age limits Technical paper (Haag Engineering Co.)
[4] Health and Safety Laboratory (HSL) 2010 Tower crane incidents worldwide Research Report RR820 Health and Safety Executive (HSE)
[5] Ali M K and Mohamad M I 2016 Crane Failure and Accident in Construction Construction Management, Geotechnics and Transportation Vol 2
[6] Radlov K 2012 Analysis of the risk of accident of a mobile tower crane with a non-rotating tower caused by technical malfunctions Proceedings of the VII International Scientific Conference - Civil Engineering Design and Construction (Varna, Bulgaria) (in Bulgarian)
[7] Zavadsky Yu V 1976 Statistical processing of the experiment: Textbook (Moscow: Vysshaya Shkola) (in Russian)
[8] Dimitrov K and Danchev D 1994 Reliability of construction machinery and systems (Sofia: Tehnika) (in Bulgarian)
[9] Kalinov K 2002 Probability Theory and Statistics (Sofia: NBU) (in Bulgarian)
[10] State Agency for Metrological and Technical Surveillance 2010 Ordinance on the Safe Operation and Technical Supervision of Lifting Equipment (Sofia, Bulgaria) (in Bulgarian)