A Taxonomic Analysis of Mobile Crane-related Accidents in Construction Industry for CPS-based Simulation

Congwen Kan¹, Peiyao Zhang², Yihai Fang³, Chimay J. Anumba⁴, John I. Messner⁵

1) Ph.D. Student, Rinker School of Construction Management, University of Florida, Gainesville, FL, USA. Email: congwen.kan@ufl.edu
2) Ph.D. Student, Department of Construction Management, Tsinghua University, Beijing, China. Email: zhangpy14@mails.tsinghua.edu.cn
3) Ph.D., Lecturer, Department of Civil Engineering, Monash University, Clayton, Australia. Email: yihai.fang@monash.edu
4) Ph.D., Prof.& Dean, College of Design, Construction and Planning, University of Florida, Gainesville, FL, USA. Email: anumba@ufl.edu
5) Ph.D., Prof., Department of Architectural Engineering, the Pennsylvania State University, University Park, PA, USA. Email: jmessner@engr.psu.edu

Abstract:

Construction is considered one of the most hazardous industry sectors due to the high accident rates encountered. Mobile cranes, as an essential component in many construction projects, are associated with a large number of injuries and fatalities. Although numerous safety measures have been undertaken and stricter safety regulations have come into effect, catastrophic crane accidents continue to occur. One of the underlying reasons for this persistent problem is the lack of a commonly accepted classification and pattern of accident occurrences. To gain sufficient insight into mobile crane-related accidents, and to establish key focus areas for future control, 916 mobile crane fatality narratives from the year 2006 to 2016 have been reviewed and investigated on the Occupational Safety and Health Administration (OSHA) website. This information was organized into groups using a scientific taxonomic process involving observation, description and classification of the data. The resulting pattern is presented with interpretation regarding each level and limitations of the information, and the pattern is intended to feed into a Cyber-Physical Systems (CPS) based mobile crane simulation tool. The results of this study are expected to expand the information base of mobile crane-related accidents, provide foundations for the CPS-based mobile crane simulation tool, and to help crane manufacturers, owners, and operators to make better risk-informed decisions regarding crane operations.

Keywords: mobile crane, safety, taxonomic analysis, construction industry, CPS, simulation

1. INTRODUCTION

The construction industry has long been criticized for its high accident rates. In the United States, the construction industry accounts for the most worker deaths out of all industries. In 2015, out of 4,379 worker fatalities in the private sector, 937 or 21.4% were in construction (OSHA, 2015). Among all safety risks on construction sites, machinery poses significant threats to workers around them. According to Hinze and Teizer (2011), one quarter of the construction worker fatalities are the result of collisions, struck-by accidents, and rollovers caused by various machinery. Cranes, as a central component in most construction projects, are associated with a large fraction of construction deaths. It was reported that construction fatalities in which cranes are involved account for up to one third of the total fatalities (Neitzel et al., 2001). Accidents caused by the operation of cranes have posed serious problems as, once accidents occur, occupational fatalities and economic losses can be substantial (Zhang et al., 2013). Although numerous safety measures have been undertaken and more strict safety regulations have come into effect, catastrophic crane accidents continue to occur. One of the underlying reasons for this persisting problem is the lack of a commonly accepted classification and pattern recognition of accident occurrences.

Several researchers have consistently explored approaches to enhance the safety of crane operations by analyzing crane-related fatalities. Suruda et al. (1999) examined OSHA’s Integrated Management Information System (IMIS) database to identify the number of fatal accidents involving cranes for the period of 1984 to 1994 and to determine their causes. For the years in question, they found 479 accidents involving 502 fatalities. It was pointed out that electrocution contributed to most of the crane-related fatalities, comprising 39% reported in that period (Suruda et al., 1999). Another taxonomic study on crane-related fatalities done by Shepard et al. (2000) examined the IMIS database for almost the same time period, from 1985 to 1995. The author found over 500 fatalities and established a taxonomy for these incidents. Similar to Sureda ‘s study, Shepard et al. (2000) found that power line contact by the crane represented 36% of the fatal events studied.
Among all types of cranes, mobile cranes take up a significant proportion of the total fatalities (Spear, 2008). According to OSHA’s website, 937 workers lost their lives at work in 2015. Of the total 937 deaths, 505 were related to mobile cranes (OSHA, 2015). This number implies that around 54% of the fatalities are associated with mobile cranes. Unlike tower cranes that are situated at a fixed location and operate within a given space, mobile cranes move freely across a construction site to perform lifting tasks. Due to their on-site mobility, mobile cranes are riskier than other types of cranes (Al-Humaidi and Hadipriono-Tan, 2009). Different from the previous taxonomic studies, this study exclusively focuses on mobile cranes. The inclusion of other types of crane, e.g. tower crane, overhead crane, gantry crane…etc. was based on the fact that (a) mobile cranes are riskier than other types of cranes in nature, as previously mentioned, (b) the operator qualification and certification requirements are not exactly the same, (c) a number of the most significant provisions of the OSHA standard (such as those covering ground conditions, proximity to power lines, work area control, and level positioning) differ between different types of cranes.

Thus, to gain sufficient insight into mobile crane-related accidents, and to establish key focus areas for future control, this paper examined almost 1,000 mobile crane fatality narratives from the year 2006 to 2016 from OSHA’s website. This information was reviewed, investigated, and organized into a pattern using a scientific taxonomic process involving observation, description, and classification of the data. The resulting pattern of accident occurrences is presented with interpretation regarding the application, and five key mobile crane failure modes were concluded out of the pattern. These failure modes are intended to feed into a Cyber-Physical Systems (CPS) based mobile crane simulation model. In order to do this, regulations from the OSHA were reviewed and estimation was made on the safety thresholds for each of the potential failure modes to avoid the afore-defined failure modes. These thresholds have been integrated with a CPS-based mobile crane simulation model, which was developed in Unity3D. The concluding part of this paper discusses the benefits of this study, and its future directions.

2. METHOD

This current study follows a similar method to Shepard et al. (2000)’s study described above. However, these two studies differ in several aspects. In the first place, the database involves the years from 2006 to 2016, whereas the dataset used in the other study ended in 1994. Secondly, the data in the earlier study was based upon the IMIS narrative reports of fatalities related to cranes in general, while the investigation in this current study focuses on accidents related to mobile cranes only. Furthermore, this study is intended to complement the earlier work of others by classifying the most recent accidents by proximal causes as well as OSHA citations and regulations.

Using the same OSHA database, this study established a taxonomy for 325 mobile crane-related accidents for a different time period. The authors searched the IMIS database for all fatal and non-fatal accidents from 2006 to 2016 investigated by OSHA involving mobile cranes in the construction industry. By searching the database for cases using the key word "crane", 916 IMIS narratives were identified for the covered year. These were then reviewed to confirm that the accident record is directly associated with mobile crane operations in the construction industry.

Before reviewing the 916 accident records, a clear scope on “construction work” and “type of crane” was defined. For “construction work”, a distinction was drawn between construction work in the construction industry and other industries. In this study, construction work was defined as consisting of a process of attaching, assembling and disassembling a vast variety of materials to form a building or other structure. Construction work performed in certain industries was excluded from being considered. The industries include railroads, shipbuilders, electric utilities, and companies that install signs in buildings under construction. For “type of crane”, since "crane" was the only key word that was used when searching the IMIS database, accident cases related to all types of crane were presented. Two rules were followed to exclude all irrelevant cases. Firstly, if the crane type was declared in the accident record, as a type of mobile crane (e.g. truck crane, crawler crane…etc.), related accidents would be counted as valid data. Secondly, if the crane type was not declared in the accident record, judgments were made based on the authors’ experiences. If a case description clearly distinguished itself as mobile crane-related accident, the data would be counted and the crane type was labeled as “mobile crane – not specified in the record”. If the authors cannot tell if a case is specifically related to mobile crane only, the data will still be counted, and the crane type was labeled as “unknown”. The definition of the scope with respect to controversial cases was further delineated while further analysis was made and/or problem arose. Using fewer keywords when searching for the data and excluding all the irrelevant cases manually helped to minimize the incongruous result of the study.

Of the 916 case narratives that were reviewed, the authors identified 325 as being mobile crane related. This selection of case narratives was reviewed, information was extracted and summarized based on the following eight categories: (a) OSHA reference number for the incident, (b) date of the incident, (c) number of fatalities, (d) type of the mobile
crane involved, whether if it’s a truck base or crawler base, and whether if it’s hydraulic boom or lattice boom…etc., (e) construction operation being performed by the mobile crane, (f) occupation of the injuries, (g) proximal cause of the incident, and (h) contributing factors by the proximal causes.

3. RESULTS

3.1 Proximal Causes and Contributing Factors

Based on the information extracted, five mutually exclusive proximal causes of mobile crane-related accidents were used for classifying the 325 cases. The occurrences and percentages caused by various types of incidents were also counted and calculated, as shown in Table 1 in order of frequency. Based on the narratives provided in the database, the authors were able to identify the contributing factors for each of the proximal causes and elucidate the details of these breakdowns, as shown in Figure 1.

Table 1. The proximal causes of mobile crane-related accidents (2006-2016)

<table>
<thead>
<tr>
<th>Proximal Causes</th>
<th>Occurrences</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Struck by</td>
<td>194</td>
<td>49%</td>
</tr>
<tr>
<td>Electrocution</td>
<td>38</td>
<td>10%</td>
</tr>
<tr>
<td>Crane tip-over</td>
<td>38</td>
<td>10%</td>
</tr>
<tr>
<td>Falls</td>
<td>35</td>
<td>9%</td>
</tr>
<tr>
<td>Failure of boom/cable</td>
<td>20</td>
<td>5%</td>
</tr>
<tr>
<td>Sum</td>
<td>325</td>
<td>100%</td>
</tr>
</tbody>
</table>

Figure 1. Mobile crane-related accidents by proximal causes and contributing factors
3.2 OSHA Citations and Requirements

OSHA standards concerning these five proximal causes were studied and requirements that address the problems were discussed as follows:

(1) Struck by

As indicated in the previous section, struck by is dominantly the leading cause of mobile crane-related accidents. The contributing factors for this cause include run over by moving crane, hit by crane parts during operation, load dropped, hit while assembling/disassembling, rigging failure, load strike, accelerated movement, and crane hit by vehicles or other equipment.

Fatalities that result from workers being struck by can be avoided under Sec. 1926.1424, work area control. This section requires that (a) workers who are near equipment with a rotating superstructure be trained in the hazards involved, (b) employers mark or barricade the area covered by the rotating superstructure, and (c) the operator be notified whenever a worker must enter that area and instructed not to rotate the superstructure until the area is clear. Accidents that involve employees being struck or crushed during assembly or disassembly are addressed in Sec. 1926.1403-1926.1406. These sections require employers to follow specific safe-practice procedures, and to address a list of specific hazards. Also, assembly and disassembly of a crane must be supervised by an individual who is well qualified to ensure that the requirements of these provisions are properly implemented, and the individual should take necessary actions to protect workers against that danger. In addition, there are also a set of rules addressing equipment failures that can result in the load striking a worker. Such accidents are directly addressed by Sec. 1926.1425, keeping clear of the load, and Sec. 1926.1426, free fall/controlled load lowering.

(2) Electrocution

Electrocution ranks second as a proximal cause. It should be noted that in previous taxonomic studies involving all types of cranes, electrocution was always the leading cause of crane-related accidents. In this study, there were only 38 incidents identified to be electrocution-related. This represents only 10% of the whole accidents. The discrepancy in number could possibly be due to the size of the mobile crane in nature.

The factors identified as contributing to this cause, failing to maintain required clearance and boom/cable contact, are addressed by Sec. 1926.1407-1926.1411. These sections were designed to avoid the failure of maintaining the OSHA-specified distance from energized power lines while cranes are being assembled, disassembled, operated, or while they travel under power lines. They contain requirements for working near energized power lines and requirements pertaining to the operation of the equipment. The OSHA standard delineates systematic, reliable procedures and methods that employers must use to prevent a safe clearance distance from being breached. If maintaining the safe clearance distance is infeasible, additional protections are required, including grounding the equipment, covering the line with an insulating sleeve, and using insulating links and nonconductive tag lines.

(3) Crane tip-over

Crane tip-over is potentially caused by factors such as overloading, improper use of outriggers, insufficient ground conditions, and improper operation. Section 1926.1417, operations, includes provisions to prevent from overloading. This section prohibits the equipment from being operated in excess of its rated capacity, and includes procedures for ensuring that the weight of the load is reliably determined and within the equipment's rated capacity. Section 1926.1404(q) has requirements for outrigger/stabilizer use that will ensure that outriggers and stabilizers provide stability when a load is lifted. Section 1926.1402 contains requirements to ensure sufficient ground conditions, which will prevent crane tip-over.

(4) Falls of people

Accidents caused by falling followed close behind electrocution and crane tip-over, with the three major contributing factors being lack of protective measures, improper worker behavior, and due to improper operation of the crane operator. Protection against falling from equipment is addressed by Sec. 1926.1423, fall protection. Regulations in this section are mostly for tower cranes, such as providing safe access to the operator work station, providing boom walkways, handholds, and grab-rails. The regulation contains fall-protection provisions tailored to assembly and disassembly work, which also apply to mobile cranes. Section 1926.1431, hoisting personnel, addresses fall protection when employees are being hoisted.
(5) Failure of boom/cable

Failure of boom/cable poses the least threat of mobile-crane related accidents. There were 20 out of 325 counted to be related. It should be noted here that failure of boom/cable causes struck by hazard. However, if the accident was due to machinery failure originally, it would be counted towards the failure of boom/cable instead of struck by. In this case, loss or damage of screw, boom failure, and cable failure were identified as the contributing factors for failure of boom/cable.

Accidents resulting from the boom or cable failure are addressed in a number of provisions. For example, the standard includes requirements for (a) proper assembly procedures (Sec. 1926.1403), (b) boom stops to prevent booms from being raised too far and toppling over backwards (Sec. 1926.1415, Safety devices), (c) a boom-hoist limiting device to prevent excessive boom travel, and (d) an anti-two-block device, which prevents overloading the boom from two-blocking (Sec. 1926.1416, Operational aids). Also, the inspection requirements (Sec. 1926.1412) detect and address structural deficiencies in booms before an accident occurs. Cable failure will be avoided by compliance with sections such as Sec. 1926.1413, wire rope inspection, and Sec. 1926.1414, wire rope selection and installation criteria.

All the OSHA citations discussed in this section are summarized by proximal causes, as presented in Table 2. Other information extracted from the data includes types of the crane associated with the accidents, frequency of mobile crane-related accidents by construction operations, and victim’s occupation. These results are not discussed in this study since they are irrelevant to the model integration, which is discussed in the remainder of this paper.

<table>
<thead>
<tr>
<th>Proximal Causes</th>
<th>Citations</th>
<th>Citation Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Struck by</td>
<td>Work area control</td>
<td>Sec. 1926.1424</td>
</tr>
<tr>
<td></td>
<td>Assembly or disassembly</td>
<td>Sec. 1926.1403-1926.1406</td>
</tr>
<tr>
<td></td>
<td>Keeping clear of the load</td>
<td>Sec. 1926.1425</td>
</tr>
<tr>
<td></td>
<td>Free fall/controlled load lowering</td>
<td>Sec. 1926.1426</td>
</tr>
<tr>
<td>Electrocution</td>
<td>Working near energized power lines</td>
<td>Sec. 1926.1407-1926.1411</td>
</tr>
<tr>
<td>Crane tip-over</td>
<td>Prevent from overloading</td>
<td>Section 1926.1417</td>
</tr>
<tr>
<td></td>
<td>Outtrigger/stabilizer use</td>
<td>Section 1926.1404(q)</td>
</tr>
<tr>
<td>Falls</td>
<td>Fall protection</td>
<td>Sec. 1926.1423</td>
</tr>
<tr>
<td></td>
<td>Hoisting personnel</td>
<td>Section 1926.1431</td>
</tr>
<tr>
<td>Failure of crane</td>
<td>Proper assembly procedures</td>
<td>Sec. 1926.1403</td>
</tr>
<tr>
<td></td>
<td>Safety devices</td>
<td>Sec. 1926.1415</td>
</tr>
<tr>
<td></td>
<td>Operational aids</td>
<td>Sec. 1926.1416</td>
</tr>
<tr>
<td></td>
<td>Inspection requirements</td>
<td>Sec. 1926.1412</td>
</tr>
<tr>
<td></td>
<td>Wire rope inspection</td>
<td>Sec. 1926.1413</td>
</tr>
<tr>
<td></td>
<td>Wire rope selection and installation criteria</td>
<td>Sec. 1926.1414</td>
</tr>
</tbody>
</table>

4. INTEGRATION OF SAFETY RULES INTO SIMULATION MODEL

4.1 Mobile Crane Operation Simulation Model

The simulation model is a construction site model incorporating both the crane model and the surrounding site environment. The software environment selected to simulate the virtual model, includes (a) Autodesk Revit for creating the building structure on site, (b) SketchUp for editing the mobile crane model, material stacks, workers and other related site components, and (c) Unity 3D for creating the terrain and rendering the whole model.

The 3D mobile crane model, and other essential jobsite components such as material stacks, workers, site office, etc. were obtained from the SketchUp warehouse. After downloading the preliminary crane model, measures were taken to break down the model into parts to allow each part of the crane to move freely in the virtual model as they do in the physical world. For instance, the model of a truck hydraulic boom crane was broken down into the base, crane body, boom, hoist line and hook, as shown in Figure 2. The building structure model, a 3-story steel framing structure created
in Autodesk Revit, together with crane model and all the other site component models in SketchUp are exported as fbx file format and later imported into the selected virtual interface.

The Unity 3D software was selected as the virtual interface for site model development. Unity 3D is a game engine that supports cross platform scripting and can be used to create an as-is physical environment, such as terrain texture and the trees. The afore-created building model, crane models, and site component packages were then imported into Unity3D to integrate with the site model. The site arrangement is modelled based on information obtained from a real construction site. Figure 3 shows a screenshot of the model.

![Crane model in parts](image1)

![Simulation model in Unity 3D](image2)

**Figure 2. Crane model in parts**

**Figure 3. Simulation model in Unity 3D**

### 4.2 Safety Threshold Estimation

In the earlier part of this paper, five proximal causes of mobile crane-related accidents were summarized by analyzing the accident records, and OSHA regulations concerning these causes were studied. Based on the information obtained from the regulations, safety threshold estimation was made in order to embed the safety constraints in the virtual model, thus to avoid these potential failures.

First of all, the authors addressed *electrocution* hazards by specifying the minimum distance that must be maintained between a mobile crane and an energized power line. According to OSHA’s citation Sec. 1926.550 (a) (15), for lines rated 50 kilovolts (kV) or below, the minimum distance was 10 feet. For lines over 50 kV, the minimum distance was generally 10 feet plus 0.4 inches for each 1 kV over 50 kV.

There is no individual safety threshold defined for the *struck by* hazard. It should comply with the clearance defined to avoid *electrocution* since the safety threshold here is also defined to avoid collisions. As indicated in the previous section, many assembly/disassembly accidents occur when sections of the crane unexpectedly move and strike or crush an employee who is assembling/disassembling the crane. In this study, the authors addressed this hazard by identifying hazardous areas and prohibiting employees from being present in these areas. Section 1926.1435(b)(2), addresses the hazards associated with crew members located in certain dangerous areas. Employees must not be in or under the jib, rotating portion of the crane during erecting, dismantling operations until the crane is secured in a locked position.

The safety thresholds defined to deal with the *crane tip-over* hazard in this study are in line with the first two regulations. Firstly, restrictions have been applied to the maximum load the crane is allowed to pick up. This load restriction is adjustable based on the length of the boom and the angle of the boom while it is lifting. This set of numbers could be obtained from the mobile crane manual. Secondly, the levelness of the crane was also measured through monitoring the base of the crane. While the crane moves across the site, the elevation difference is obtained through measuring both sides of the crane base. The restriction was set not to exceed 15 degrees; while the crane is static and utilizes outriggers, the same restriction applies to both outriggers and the base of the crane.

There is no specific safety threshold assigned to tackle the *failure of boom/cable* hazard in this study. Aside from meeting all the OSHA requirements dealing with operational factors, insights could also be gained from the crane manufacturer’s perspective, since the hazard also arises from equipment failure.

### 4.3 Safety Rule Integration

Based on the regulations reviewed and the thresholds defined in the last section, three types of hazards were addressed. Their detailed representation in the simulation model are presented as follows:
(1) Collision

Collision hazard was addressed through defining the minimal clearance between the mobile crane model and any of the surrounding site components. The clearance was defined as the closest distance between the surface point of each of the objects in this study. Figures 4(a) and 4(b) show how the clearance is measured, and the minimal clearance in this study was set to 10 feet, as afore-mentioned. Whenever the crane breaks this “10 feet safety clearance” rule and gets too close to something (e.g. workers, building structures, material stack…etc.), a warning is triggered and the site components which are subject to the collision hazard will be highlighted in red.

![Figure 4. Collision detection in isometric view (a) and top view (b)](image)

(2) Overloading

Overloading hazard was addressed by setting a limitation on the load being lifted at a specific length of boom extension. The limitation on the load and the weight of the targeted item are shown on the screen when the crane is about to lift anything, as shown in Figure 5.

![Figure 5. Load limitation](image)

(3) Crane tip-over

The crane tip-over hazard is addressed through monitoring the base of the crane. While the crane is moving across the site, the elevation differences are obtained through measuring the two sides of the crane base. The restriction was set not to exceed 15 degrees; while the crane is static and utilizes outriggers, the same restriction applies to both outriggers and the base of the crane. The interpretations are presented in Figure 6 and Figure 7.

![Figure 6. Outrigger levelness](image)  ![Figure 7. Crane levelness](image)
These three demonstrations of safety rule integration are explorations on how the information base of mobile crane-related accidents aids in building the virtual simulation model. This virtual model, together with the safety rules integrated, represents the virtual interface of a CPS-based model. Approaches were made available to monitor the operation of a mobile crane on a physical construction site, which is the physical interface of the CPS-based model. The CPS method enables the information to flow bi-directionally between the virtual interface and the physical interface. For example, if any potential hazard is detected based on the pre-defined rules in the virtual interface, a warning message would be sent to the crane operator on site through visual, auditory warning or haptic cues. It can be seen as an informative approach that provides information on the monitored state of the mobile crane and of the environment. Details on how a CPS-based model works can be obtained from Kan et al. (2017).

5. SUMMARY AND CONCLUSIONS

This paper investigated proximal causes of mobile crane-related accidents by studying narratives from OSHA’s IMIS database. The accident occurrences were organized into a taxonomy and OSHA regulations concerning the identified causes were studied. Regulations were reviewed and an estimation on the safety thresholds was made to avoid these potential hazards. This was followed by the establishment of a set of safety rules for each potential failure that can be embedded within a CPS-based mobile crane simulation model. The results of this study are expected to expand the information base of mobile crane-related accidents and to provide the foundations for the CPS-based mobile crane simulation tool. With the capability of enhancing bi-directional coordination between physical components and their virtual representations, the CPS tool offers advantages in effective planning, proactively monitoring crane operations, providing rich feedback to crane operator and, in turn, ultimately reducing or avoiding mobile crane failures by helping crane manufacturers, owners, and operators to make better risk-informed decisions regarding crane operations.

Future work will focus on the validation of the simulation model and conducting field tests on a real construction site to demonstrate the practical functionality and benefits of the system. Constraints that will need to be addressed include difficulties in making precise estimation on the safety thresholds and adjusting the thresholds based on different types of the mobile cranes. Other explorations include comparing the resulting accident occurrence pattern of this study and previous taxonomic studies concerning cranes, and discussing the changes based on changes in OSHA regulations as well as technological advancements.

REFERENCES


