Prefabricated building hoisting safety risk identification and control

Ji Yingbo, Li Yanyao, Liu Yan

School of Civil Engineering, North China University of Technology, Beijing 100144, China

Abstract: At the construction site of the prefabricated building, the lifting work is large, the duration is long, the shape of the components is irregular and the weight is large, and the work requires a high concentration of attention. Various reasons lead to frequent hoisting accidents at the construction site. In order to reduce the occurrence of hoisting accidents on the construction site of the prefabricated building, this paper identifies the hazard sources in the hoisting operation process through the method of accident statistics and questionnaire survey, and analyzes the causes of the hoisting safety accidents by means of system thinking to establish the hoisting of the assembled building. Through the qualitative and quantitative analysis, the safety accident tree analyzes and summarizes the main factors affecting the safety of the assembled building hoisting, and draws important hazard sources that have a great impact on the hoisting safety, and then proposes targeted control measures and recommendations. Improve the hoisting environment at the construction site.

1. Introduction

Some or even all of the components of prefabricated buildings are produced in prefabricated factories and then transported to the construction site for hoisting operations, which improves the messiness of traditional construction sites, but also increases the number of lifting operations. In addition, owing to the large volume and weight of prefabricated components and irregular shape, the safety risk management of prefabricated building hoisting has become a research hotspot of field construction management.

At present, foreign research on fabricated buildings involves the fire resistance [1] and earthquake resistance [2-3] of buildings. The research of fabricated buildings in China mainly lies in three aspects of cost [4-5], schedule [6], quality [7]. There are few studies on construction safety, and existing safety research mainly focuses on the establishment and evaluation of construction process safety index system. Chang Chunguang et. al. [8] calculated the safety risk accident rate and the importance of basic events based on the BDD structure, and realized the qualitative and quantitative analysis of the safety risk of the prefabricated building construction process. Chen Wei et. al. [9] combined application of Analytic Hierarchy Process (AHP) and Grey Clustering Evaluation Method to construct a safety assessment index system for assembly construction, sort the indicators, and take corresponding measures to reduce the probability of safety accidents. Huang Guilin et. al. [10] combined with the safety risk factors of the construction process of the assembled house, constructed the safety risk index system of the assembly house construction process, combined with the actual case, objectively evaluated the safety risk status and diagnosed the safety hazard. Liu Mingqiang et. al. [11] used 5 elements of people-machine-material-method-environment to determine the prefabricated building safety warning index system and verified the effectiveness of the model through relevant data, and improved the level of assembly building
hoisting operations. Miao Zhen et al.[12] used BIM and RFID method to manage the construction of the prefabricated building, personal safety, foundation construction safety, temporary support arrangement and hoisting safety. Pan Dan et al. [13] and other comprehensively adopted the rooted theory, entropy weight method and structural equation model to construct the safety performance evaluation index system according to the construction, and applied the model to the actual project evaluation, which verified the reliability of the model.

In the existing research on the safety index system of prefabricated building construction in China, the hoisting safety is only part of the evaluation index system, and no further research has been carried out for itself. However, the hoisting accident is one of dangerous sources that is relatively serious and difficult to control in the prefabricated construction site. There are many causes, so it is necessary for in-depth research. In this paper, the hoisting accident is taken as the research object. Through the accident statistics and expert interview methods, the hoisting safety hazard source is identified, and the hoisting safety accident tree of the assembled building is constructed. Through the calculation and analysis of the accident tree, the major dangerous sources are selected and targeted measures are carried out to effectively reduce the incidence of hoisting safety accidents.

2. Safety accident tree of prefabricated building hoisting work

2.1 Introduction

Accident Tree Analysis, also known as Fault Tree Analysis (FTA)[14], is one of the important analytical methods for safety system engineering [15]. Starting from the top-level accident, and analyzing the reasons for the accident step by step, and then the basic events related to the accident are obtained. Through the logical relationship between the events, the accident tree is drawn, and the safety hazard of the accident is found. Based on the combination of qualitative and quantitative methods, it is concluded that the impact of each basic event on the occurrence of the top event can prevent the occurrence of the accident and promptly propose emergency measures after the accident.

Accident tree analysis method is an important evaluation method in safety system engineering. It can not only identify and evaluate the dangers of various systems, but also reveal the potential causes of accidents. In China, it has been widely used in safety assessment, safety management, accident prevention and other aspects of industries like mining, energy, construction, transportation, etc. [16]

2.2 Assembling accidents in prefabricated building hoisting operations

According to the “2015 National Housing Municipal Engineering Production Safety Accidents” published by the Ministry of Housing and Urban-Rural Development of the People’s Republic of China [17] and the literature analysis on the construction safety production situation, combining with the characteristics of the construction of the assembly-type construction project, the main types of construction safety accidents with high frequency of occurrence are combed: falling, object strikes, component hoisting, hoisting machine damage, tower crane collapse.

(1) Falling. Due to the rapid development of high-rise buildings in recent years, falling has become one of the high-frequency safety accidents in the construction industry. For the prefabricated buildings, scaffolding in traditional building construction has not been used due to its special construction technology, but high-altitude operation still exists. In the process of assembling the outer wall, if the frontal protection measures are not in place, it is easy to cause the staff to fall accidents at high altitude.

(2) Object strikes. Due to the requirements of the hoisting operation of the prefabricated building, the fence cannot be set up on the periphery of the building, and the hoisting process cannot avoid the occurrence of various parts falling from high places, causing damage to the construction workers below.

(3) Component hoisting. The hoisting operation is to lift the prefabricated components to the design position by the tower crane. During the hoisting process, problems such as unreasonable lifting point setting and deformation of the lifting point may occur, and the components may not be safely hoisted to the expected position to collide with other buildings, or components may drop down and cause physical damage to the decentralized staff.

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(4) Hoisting machine damage. Due to the aging of parts due to long-term work, some hoisting machines have not been inspected in time before the operation, resulting in sudden failures during the operation, resulting in unsuccessful work and serious injury.

(5) Tower crane collapsed. During the installation and disassembly of the tower crane, the tower crane may collapse due to equipment failure or improper operation of the operator, causing damage to surrounding buildings and construction personnel.

2.3 Prefabricated building hoisting safety accident tree
Due to the lack of research on the safety accidents of prefabricated building hoisting, according to the results of a large number of literature analysis, combined with the "case analysis of construction safety accidents" [18], the direct causes of safety accidents caused by lifting operations can be divided into three categories: improper personnel operation, Equipment failure and on-site management confusion. This paper selects 10 safety commanders, tower crane drivers and on-site safety administrators who have participated in the hoisting work for a long time to conduct a questionnaire survey. According to the logical relationship between basic events, intermediate events and top events, the safety of assembled building hoisting is drawn. The accident tree is shown below.

![Figure 1: Assembly building hoisting safety accident](image)
Comment: T—Assembled building hoisting safety accident; M1—Improper personnel operation; M2—Equipment failure; M3—Management confusion; M4—Worker's own cause; M5—Equipment running unexpected failure.

| No. | Event                                                                 | Probability |
|-----|-----------------------------------------------------------------------|-------------|
| X1  | No professional and safety training for workers                       | 0.0194      |
| X2  | Unreasonable worker scheduling leads to fatigue work                  | 0.0718      |
| X3  | Operator has no corresponding qualification                            | 0.1971      |
| X4  | Low security awareness                                                | 0.0904      |
| X5  | Illegal operation                                                     | 0.0251      |
| X6  | Overload lifting                                                      | 0.0927      |
| X7  | No security check at the time of admission                             | 0.0310      |
| X8  | Long-term operation of equipment leads to aging of parts              | 0.0139      |
| X9  | No regular security checks and repairs                                 | 0.0620      |
| X10 | Managers did not seriously fulfill management responsibilities         | 0.0339      |
| X11 | No special hoisting plan                                              | 0.1146      |
| X12 | Lack of professional managers on site                                  | 0.0649      |
| X13 | Safety measures are not in place                                       | 0.1031      |
3. Analysis of hoisting safety accident tree in prefabricated building

3.1 Accident tree qualitative analysis

(1) Minimum cut set

Use Boolean algebra to find the minimum cut set:

\[ T = M_1 + M_2 + M_3 = X_1 + X_2 + M_4 + X_6 + M_5 + X_{10} + X_{11} + X_{12} + X_{13} + X_{14} = X_1 + X_2 + X_3 X_4 X_5 + X_6 + X_7 X_8 X_9 + X_{10} + X_{11} + X_{12} + X_{13} + X_{14} \]

The minimum cut set is:

- \( E_1 = \{X_1\} \)
- \( E_2 = \{X_2\} \)
- \( E_3 = \{X_3, X_4, X_5\} \)
- \( E_4 = \{X_6\} \)
- \( E_5 = \{X_7, X_8, X_9\} \)
- \( E_6 = \{X_{10}\} \)
- \( E_7 = \{X_{11}\} \)
- \( E_8 = \{X_{12}\} \)
- \( E_9 = \{X_{13}\} \)
- \( E_{10} = \{X_{14}\} \)

(2) Minimum path set

- \( E_1^* = \{X_1, X_2, X_3, X_6, X_7, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}\} \)
- \( E_2^* = \{X_1, X_2, X_3, X_6, X_8, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}\} \)
- \( E_3^* = \{X_1, X_2, X_3, X_6, X_9, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}\} \)
- \( E_4^* = \{X_1, X_2, X_4, X_6, X_7, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}\} \)
- \( E_5^* = \{X_1, X_2, X_4, X_6, X_8, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}\} \)
- \( E_6^* = \{X_1, X_2, X_4, X_6, X_9, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}\} \)
- \( E_7^* = \{X_1, X_2, X_5, X_6, X_7, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}\} \)
- \( E_8^* = \{X_1, X_2, X_5, X_6, X_8, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}\} \)
- \( E_9^* = \{X_1, X_2, X_5, X_6, X_9, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}\} \)

(3) The structural importance of each basic event is obtained by the obtained 9 minimum path sets:

\[ I(X_{14}) = I(X_{13}) = I(X_{12}) = I(X_{11}) = I(X_6) = I(X_2) = I(X_1) = I(X_9) = I(X_8) = I(X_7) = I(X_5) = I(X_4) = I(X_3) \]

3.2 Accident tree quantitative analysis

(1) Top event probability

According to the accident tree model and the investigation situation and data, determine the probability of occurrence of the basic event, and find the probability of occurrence of the top event. The probability of the top incident hoisting safety accident in this paper is 45.5%. It can be seen that at the construction site, the probability of hoisting safety accidents is extremely high, and corresponding measures must be taken to reduce the occurrence of safety accidents.

(2) Probability importance

The probability importance of each basic event is ranked as:

\[ X_{11} > X_{13} > X_6 > X_{14} > X_2 > X_{12} > X_{10} > X_1 > X_5 > X_4 > X_3 > X_8 > X_7 > X_9 \]

(3) Critical importance

The critical importance of each basic event is ordered as:

\[ X_{11} > X_{13} > X_6 > X_{14} > X_2 > X_{12} > X_{10} > X_1 > X_4 > X_5 > X_3 > X_9 > X_7 > X_8 \]

3.3 Accident tree result analysis

(1) The 14 basic influencing factors can be used as a typical source of danger, but cannot represent all risk factors. The superposition of any of several factors will greatly increase the probability of accidents.

(2) 10 minimum cut sets and 9 minimum path sets, indicating that there may be 10 occurrences of the top event, and each minimum cut set contains only a few basic events, which is easy to meet the conditions of the top accident. The minimum path set covers a large number of basic factors, and the prevention and control are difficult. At least five risk factors need to be comprehensively prevented.

(3) The structural importance reflects the degree of influence of the hazard source. It is clear that the key problems causing the accident are the special lifting plan, the safety protection measures and the improper operation caused by the workers themselves. For the impact of equipment and environment
on the accident, it is necessary to increase the impact of the equipment and the environment on the accident, and check the strength and prevent and control in advance.

The structural importance is used to identify the extent to which the occurrence of the basic event affects the occurrence of the top event T, regardless of the probability of occurrence of the basic event, and is only obtained by analyzing the logical relationship of the number of accidents. [19] Probability importance analysis the influence of the change of the basic event probability on the probability of occurrence of the top event. According to the probability importance coefficient of the basic event, it can analyze the situation of the basic event and reduce the occurrence of those or basic events probability can effectively reduce the probability of occurrence of the top event.[20] The critical importance is the comprehensive evaluation of the importance of each basic event from the probability of each basic event occurring and the importance of the basic time in the structure of the accident tree. [21]

According to the calculation result of the hoisting safety accident tree of the prefabricated building, the influence of the surrounding environment on the hoisting operation, the safety protection measures, the configuration of the site management personnel, the formulation of the special hoisting plan, the responsibility of the management personnel, the overloading and lifting, the safety, professional training and reasonable scheduling system of the workers, have a great impact on hoisting safety. According to the probability importance coefficient of each basic event, the top five events are unspecified special scheme for hoisting, non-conforming safety measures, overloaded lifting, ignoring the impact of surrounding environment on the operation, unreasonable worker scheduling leads to fatigue operation. The critical importance coefficient is basically consistent with the ranking of the probability importance coefficient, and the important influencing factors are the same.

4. Security risk management

According to the analysis results of the accident tree, combined with the three factors of structural importance, probability importance and critical importance, the five factors that have the greatest impact on the safety of the assembled building hoisting are that unspecified special scheme for hoisting, non-conforming safety measures, overloaded lifting, ignoring the impact of the surrounding environment on the operation, unreasonable worker scheduling leads to fatigue work. In response to these five important factors, advance prevention and post-rescue measures are proposed.

Unspecified special scheme for hoisting

The hoisting work of prefabricated buildings has a large workload and complicated work. Different hoisting operations require different types of hoisting plans, which not only reduces the probability of occurrence of safety accidents, but also speeds up the construction progress. Hoisting plan plays an important role in the overall construction process management of prefabricated buildings.

Before the construction, a corresponding special plan for the construction of the concrete building should be prepared, including the special safety plan, the emergency plan for safety production, and the fire emergency plan. And the special program needs to pass the expert argument as required. According to the characteristics of construction management technology of the prefabricated building project, the construction unit should carry out safety training and disclosure of relevant personnel on site, and clarify the risks and prevention measures of on-site lifting operations.

(2) Non-conforming safety measures

An important part of the construction process of prefabricated components during assembly is also a part of frequent safety accidents. Therefore, it is necessary to strengthen the safety management of the lifting of the construction site to meet the actual requirements of the construction site for the lifting machinery. The relevant personnel on site must wear the appropriate safety protection tools correctly.

In the hoisting process, due to the particularity of prefabricated building construction, scaffolding cannot be used for operation. So, in order to reduce the incidence of adjacent falling objects.

(3) Overloaded operations

There may be some factors influencing the overload operation of hoisting machinery, such as wrong command and judgment, lack of professional skills of drivers, emphasis on progress and cost rather than safety, improper technical scheme, and unreasonable selection of crane [22]. Due to the large number of
company construction tasks, the huge hoisting workload and hoisting environment is relatively harsh. So, in order to reduce the construction cost, the construction company often completes the large on-site workload with relatively low mechanical cost. To a certain extent, the mechanical equipment is passively overloaded, resulting in long-term damage to the mechanical equipment, then the function of mechanical operation is impaired, the safety is greatly reduced, and the machine maintenance is not timely, which is very likely to cause safety hazards. The overload of machinery is an important part of the safety management of the construction site, and should be paid enough attention to avoid the occurrence of safety accidents. [23]

(4) Ignoring the impact of the surrounding environment on the operation
For the scope of impact of the operation, it is necessary to take temporary measures with other construction work areas. Before the lifting operation is carried out, the safety hazard can be eliminated, the safety scope can be set in advance, and the modern monitoring technology is used to issue an alarm to the unsafe hidden dangers in the safety scope, so that the on-site safety management personnel can perform safety management in time.

(5) Unreasonable worker scheduling leads to fatigue work
The physiological quality of a person is an important factor influencing the behavior of the subject. The physiological qualities include psychological quality and physical quality. The cranes on the construction site need to climb to the height of tens of meters every day, and because there are risks in the climbing process, they basically need to stay at the height for at least 8 hours or longer, because they are more sensitive to the perception of the external environment. The working state of time will exert double pressure on their physiology and psychology. The work in this fatigue state will greatly affect their operational accuracy and work efficiency. Therefore, the site management personnel need to make reasonable schedule for the tower crane driver to avoid unnecessary safety incidents.

5. Conclusion
Firstly, this paper analyzes the past cases of construction safety accidents, and uses system thinking methods to trace the direct and indirect causes of hoisting safety accidents on the prefabricated building construction site, and establishes a construction-type building hoisting safety accident tree. After the accident tree is qualitatively and quantitatively combined. Analysis shows that the five main factors affecting the safety of hoisting are: unspecified special scheme for hoisting, non-conforming safety measures, overloaded lifting, ignoring the impact of surrounding environment on the operation, and unreasonable worker scheduling leads to fatigue operation.

Secondly, in response to these five safety hazards, corresponding prevention and rescue measures were made in terms of mechanical use, site management, and staffing, which greatly improved the hoisting environment at the construction site.

Finally, in the era of rapid development of information technology, it is necessary to apply relevant emerging technologies to carry out safety management on the construction site hoisting operations, optimize the site staffing, informationize the safety management of the construction site, improve work efficiency, and speed up the construction progress. Further research is still needed for this part of work later.

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