RISK IDENTIFICATION AND ANALYSIS OF PRECAST CONCRETE STRUCTURE BASED ON WORK BREAKDOWN STRUCTURE-RISK BREAKDOWN STRUCTURE

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ABSTRACT

Because the prefabricated building started late in China, and subject to management and technical restrictions, the safety problems during the construction of the prefabricated building have not been solved effectively. In view of the problems of complex environments in precast concrete structure and many influencing factors which makes the construction risks are difficult to identify. The work breakdown structure (WBS) - risk breakdown structure (RBS) method is introduced to solve the problem. By means of analyzing the investigation data of the prefabricated building accidents, its risks during construction are identified and coupled. Then the judgment matrix is obtained and the corresponding risk factors can be established. In the meanwhile, the fault tree analysis method has been being used to analyze the sensitivity of three kinds of accidents, such as falling, striking by object and electrocution. The sensitive coefficients of risk factors are calculated and sorted. The result shows that the main risk factors of falling accident are verticality deviation of component installation, deviation of component position and unsecured mechanics. The main risk factors of striking by object/equipment are insufficient strength of components supporting, overturning components and unreasonable of suspension point. The main risk factors of electrocution are improper welding operation and short circuit. Finally, corresponding control measures are put forward according to the risk accidents. The research results provided a good theoretical basis for the risk identification of prefabricated building construction.

KEYWORDS: *Precast concrete structure; fault tree analysis; work breakdown structure (WBS); risk breakdown structure (RBS); sensitivity analysis*

1.0 INTRODUCTION

The construction industry is one of the major economic industries in China. With the acceleration of urbanization in recent years, the housing demand continues to grow in

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the real-estate industry. The construction industry urgently needs to realize the industrialization production when the labor cost is becoming more and more expensive. As the main achievement of construction industrialization, prefabricated buildings provide a residential product for people which are both energy-saving and compatible with human habitation. Prefabricated buildings are fabricated in factories and assembled on site, which can effective control the quality and process of building components. It can also reduce dust pollution and noise pollution in construction site. Meanwhile, mechanized production reduces labor demand and improves production efficiency. Prefabricated buildings started earlier in Europe, the United States, Japan, Singapore and other developed regions and countries. According to relevant statistics, the proportion of prefabricated houses and ordinary houses have reached a high level in developed regions and countries. The specific data is shown in Figure 1 (Tang, 2015).

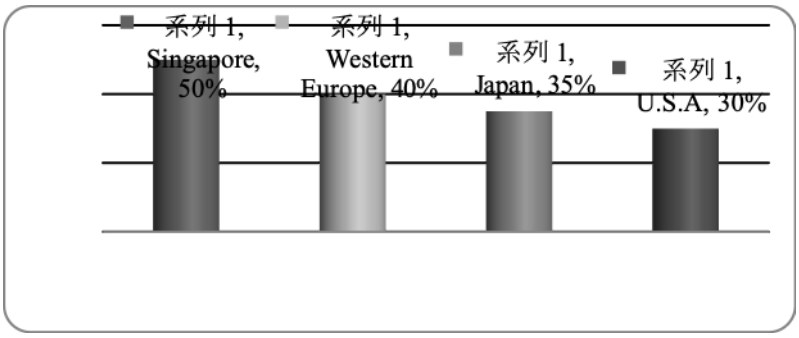

Fig 1. Proportion of prefabricated building

With the acceleration of urbanization in China and the inherent advantages of prefabricated building, the prefabricated building started to develop vigorously in our country. In recent years, many prefabricated concrete buildings in the mainland of China were caused widespread concern in the construction industry, such as Shenzhen long liberte, Zhangjiajie blue harbor project, Qingdao Vanke ITA. According to the prefabricated housing construction information statistics of Qingdao Vanke ITA building 3, building 7, the construction period is shortened by about 30%, the consumption of concrete, the loss of steel and the amount of water used for construction are reduced by about 60%, construction waste decreased by about 80%, on-site technical personnel decreased by about 60% (Yang, 2016) than that in traditional architecture. In February 6, 2016, it was put forward clearly in the < Central Committee of the Communist Party of China and the State Council on Further Strengthening the administration of urban planning and construction > issued that the proportion of prefabricated buildings accounted for 30% of new construction in the next 10 years (GMW, 2016). There is bound to be a sharp increase in prefabricated building under the implementation of the document.

Since 1950s, the prefabricated building was begun to implement in China. It is a kind of structural system which is studied and applied more and more in the prefabricated structure because of its good overall performance and seismic performance (Chen, Zhou, Zhang & Wu, 2012). The prefabricated concrete structure is divided into three structural systems, which are the prefabricated concrete frame structure, prefabricated concrete shear wall structure and prefabricated concrete frame-shear wall structure (Tian, Huang, Li & Yin, 2015). The prefabricated concrete frame structure becomes the most suitable form for prefabrication and assembly, because of the definite force transmission path, the high assembly rate, and the less cast-in-place operation (Zhao, 2016; Shi & Lin, 2014).

The development process of the prefabricated building system in our country still belongs to the stage of continuous exploration and development. Because of its concurrent construction in component design, production, transportation, unloading and site assembly, it is easy to stack safety risks. Simultaneously, there are a lack of experienced and skilled staffs to meet the needs of prefabricated building technology at this stage, so it is easy to cause safety accidents. At present, the research on the risk of the prefabricated building construction project is still at the initial stage. Li et al (2017) used the numerical simulation method to analyze the impact of risk factors on the assembly building construction plan from the system dynamics theory, he Screened out that the key risk sources for information was LIIBDERPS (Low information interoperability between different enterprise resource planning systems). Through the investigation and analysis of 125 safety accidents in United States assembly building, Maryam, Seyyed, Charles and Hamed (2017) found that the main reason for the safety of prefabricated building construction was the risk of falling at high altitude caused by instability between components. Based on their study, corresponding safety measures are put forward according to the construction of the part connection.

Tian (2014) summed up the key risk sources during the construction stage of the assembly type construction, which is based on the large residential community project in Shanghai, Pujiang, and formed a systematic risk management system. Liu and Liu (2015) applied the BIM technology in the prefabricated building design - construction phase, which ensured the smooth implementation of the construction schedule, and reduced the delay of construction period risk. The theory of system dynamics and the method of numerical simulation are used to evaluate the influence factors of construction safety of prefabricated residential buildings by Tang (2015). Based on the causes of safety accidents, Chen, Fu, Xiong and Yang (2016) analyzed the impact of prefabricated building construction safety factors, and searched for key security risks. In order to analyze the key factors which, affect construction safety, the method of Analytic Hierarchy Process (AHP) and grey clustering are applied. The construction safety evaluation index system and evaluation model is constructed, and it can be used to evaluate actual construction safety status of assembly type construction project.

To summarize, there are few achievements in risk identification and analysis of prefabricated building construction at present. Furthermore, the research process is mostly the mechanical application of the evaluation method, which is lacking the support of specific data. Therefore, the evaluation results are very subjective. Based on the investigation of accident data in prefabricated building construction (Wen, Wang & Wu, 2015; Maryam et al., 2017), the WBS-RBS method is used to decompose the work structure and risk source of the prefabricated concrete frame structure systematically, the related risk accidents is coupled as well. According to the corresponding logical relation, the fault tree of the assembled concrete frame structure is set up. On the basis of this analysis, the key risk factors are identified by combining sensitivity analysis, and corresponding control measures are put forward (Zhou, Gao, Cai & Zhang, 2009).

2.0 FAULT TREE ANALYSIS METHOD AND WBS-RBS DECOMPOSITION STRUCTURE

2.1 Fault tree analysis method

Fault tree analysis (FTA) is the most important analysis method of security system engineering (Danilo & Tomas, 2016). It is not only intuitive and clear, but also has clear analysis path with strong logic. First, the event which is prone to occur and the consequence is serious is regarded as the top event at the fault tree. Then, based on the cause of the system failure, the accidents thinning according to the shape of the branches gradually and the system failure is analyzed from point to point by whole to part. Finally, by analyzing the sensitivity of the minimum cut set in the fault event, the risk grade of the system is determined, and the risk factors with the greatest sensitivity coefficient are determined (Mohammed, Faisal & Zoubida, 2016).

2.2 WBS-RBS breakdown structure

WBS-RBS is an engineering risk identification method which can study the risk of construction project and the details of engineering construction at the same time (Rafele, Hillson & Grimald, 2005). The risk identification process mainly includes as the following steps:

(1) Construct a work breakdown structure (WBS)
The whole project is decomposed systematically and divided it into several independent operating units. The structure is shown in Figure 2.

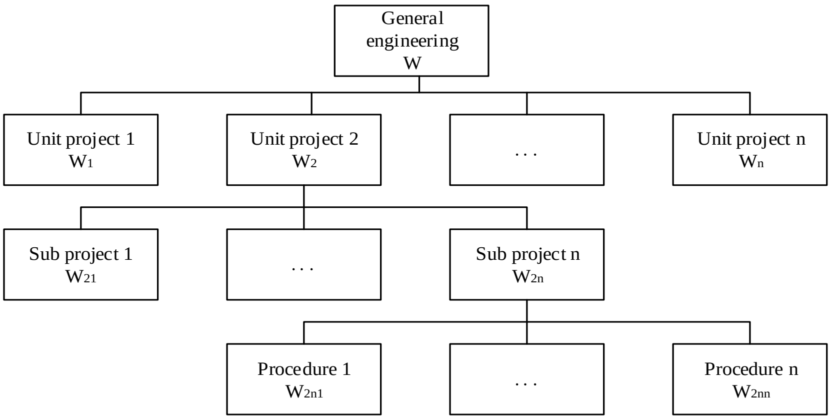

Fig 2. Work breakdown structure

(2) Construct a risk breakdown structure (RBS)

According to risk category, the risk factors in construction stage are decomposed until to the root cause of all kinds of risks. The structure is shown in Figure 3.

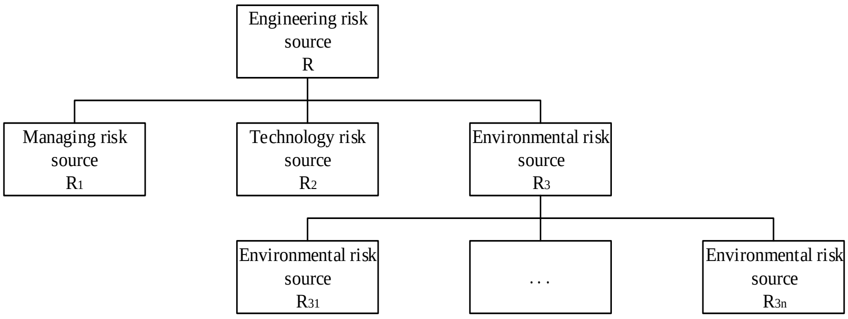

Fig 3. Risk breakdown structure

(3) Establish WBS-RBS coupling matrix

The coupling matrix is constructed by using WBS as row vector and RBS as column vector, and the relationship between forming process and basic risk source is mapped. As shown in table 1 Among which, "0" represents there is no risk factor for the coupling, "1" means that the coupling is a risk factor. And the "1" at different locations represents different risk factors (Wang, Liu & Qi, 2015).

(4) Fault tree plotting

According to the logic relation of the fault tree, the treetop event is taken as the starting point and the causes events which cause the upper level event to occur is analyzed layer by layer. According to the logical relation, the upper level events and the underlying events are connected by logical gates until the required depth of study is reached. Finally, the fault tree of the target event is obtained, as shown in Figure 4.

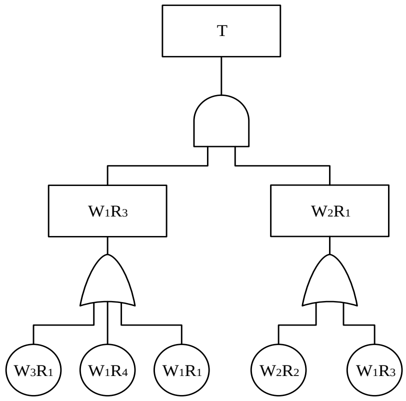

Fig 4. Fault tree

2.3 Sensitivity analysis

Sensitivity analysis is set by building model $y=f(x_1,x_2,...x_n,n=i)$ (x_i is the a attribute value of model i), and make the attribute value change within a certain range of values. Then, the change of attribute and the influence of value can be observed and studied on the output value of model (Cai, Xing & Hu, 2008).

The purpose of sensitivity analysis is to discover the basic events that contribute more to the top events in the fault tree, and the concrete calculation method is as follows.

2.3.1 Computes minimal cut sets

The minimum cut set in the fault tree is calculated by Boolean algebra method. Set it as:

$$\{K_i, i=1,2...n\} \quad (1)$$

Ki is the first i minimum cut set.

2.3.2 Probability of top event

The probability of the top event occurrence is calculated by the lower form.

$$Fs=P(T)=P(K_1+K_2+\cdots K_n)=\sum_{i=1}^{n}P(K_i)-\sum_{i<j<t-3}^{n}P(K_iK_jK_t)+\cdots+(-1)^{n-1}P(K_1K_2\cdots K_k) \quad (2)$$

$P(T)$ is the probability value of the top event T.

2.3.3 Calculation of sensitive coefficient of risk factors

The sensitivity coefficients of the basic events in the top event of the fault tree are calculated by the lower form.

$$I_g(i) = \frac{\partial F_s}{\partial F_i} \times \frac{F_i}{F_s} \qquad (3)$$

$I_g(i)$ is the sensitivity coefficient for the first i basic events.

3.0 IDENTIFICATION AND ANALYSIS OF CONSTRUCTION RISK OF PREFABRICATED CONCRETE FRAME STRUCTURE

3.1 The construction risk fault tree top event of prefabricated concrete frame structure engineering

According to the < 2016 housing and municipal engineering production safety accident briefing > which was issued by the Ministry of housing and Urban Construction of the People's Republic of China. The housing municipal engineering production safety accidents are divided into five types in 2016: fall, struck by object, lifting damage, collapsed and others (GOV, 2016). Based on the type of production safety accidents in housing and municipal engineering, and combine the characteristics of factory prefabricated production, the features of on-site lifting and splicing and construction risk literature in field study of fabricated construction projects. The construction risk of prefabricated building can be classified as five categories, which are component loading and unloading risk, lifting and splicing risk of components, falling risk, the risk of struck by object and electrocution risk.

The prefabricated building started earlier in American, and it has high socialization of production with mature standard system (Jack, Kathy & Amie, 2001). There are many researches on safety accidents in prefabricated building construction as well. The related studies have investigated 125 prefabricated building construction safety accidents in the United States, the causes of these accidents were analyzed and classified. Then, there are 6 main types of accidents in prefabricated building construction are obtained, Which are fall, strike by object/equipment, electrocution, hit by vehicle, caught in equipment/object/material, animal and insect related incidents. The percentage of all accidents in every construction cases are shown in Figure 5.

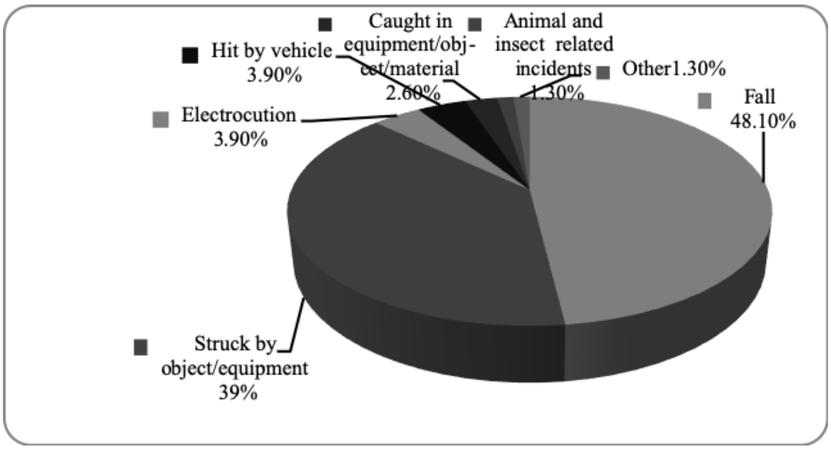

Fig 5. Classification statistics of safety accidents in overseas assembly building construction

The prefabricated building is starting late in our country, and there is no record of safety accidents in prefabricated building construction. Based on the risk analysis of prefabricated building construction in our country, and combining with the investigation and classification of construction safety accidents in prefabricated building construction in the United States. Then the study aiming at the problem of identification and analysis in prefabricated building construction risk, and falling, struck by object/equipment and electrocution is selected as the top events of the fault tree in the prefabricated concrete frame structure construction. The accident probabilities are 48.1%, 39% and 3.9% respectively.

3.2 Work breakdown structure of prefabricated concrete frame structure

In this paper, the WBS decomposition of prefabricated concrete frame structure during construction is presented. As shown in Figure 6.

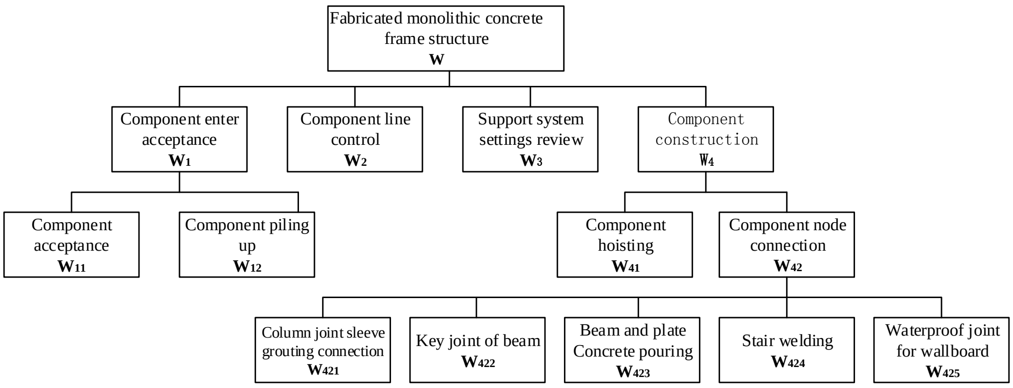

Fig 6. Work breakdown structure of prefabricated concrete frame structure

3.3 Risk breakdown structure of prefabricated concrete frame structure

According to the risk characteristics of prefabricated concrete frame structures, the risks are divided into three categories: management risk, technology risk and environment risk. Among them, management risk mainly considers the management ability of construction units, technical risk mainly considers in master-slave design stage and construction stage, and environmental risk is mainly from two aspects: policy environment and natural environment. The RBS breakdown structure is shown in Figure 7.

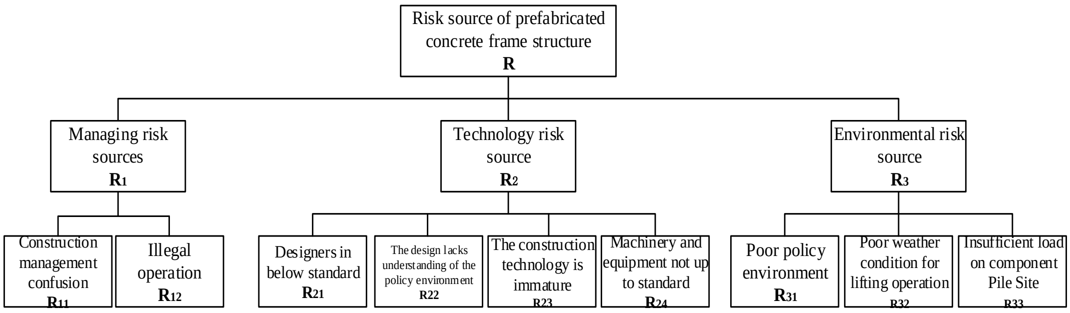

Fig 7. Risk breakdown structure of prefabricated concrete frame structure

3.4 Establishment of WBS-RBS coupling matrix for prefabricated concrete frame structures

The bottom events of the WBS and the bottom events of the RBS are individually coupled to determine whether the coupled event is present. The WBS-RBS coupling matrix of the prefabricated concrete frame structure is shown in Table 1.

Table 1. WBS-RBS coupling matrix of prefabricated concrete frame structures

		W_1		**W_2**	**W_3**	**W_4**					
		W_{11}	**W_{12}**			**W_{41}**	**W_{42}**				
							W_{421}	**W_{422}**	**W_{423}**	**W_{424}**	**W_{425}**
R_1	R_{11}	1	0	0	0	1	0	0	0	0	0
	R_{12}	0	0	0	0	1	0	0	0	0	0
R_2	R_{21}	0	0	0	0	1	0	0	0	0	0
	R_{22}	0	0	0	0	0	0	0	0	0	0
	R_{23}	0	0	1	1	1	1	1	1	1	1
	R_{24}	0	0	0	0	1	0	0	0	1	0
R_3	R_{31}	0	0	0	0	0	0	0	0	0	0
	R_{32}	0	0	0	0	1	0	0	0	0	0
	R_{33}	0	1	0	0	0	0	0	0	0	0

According to the statistical results of construction accidents in prefabricated building, the risk events or risk factors represented by "1" in the table are obtained by coupling action. $W_{11}R_{11}$: Unsecured component; $W_{12}R_{33}$: Foundation collapse; W_2R_{23}:Verticality deviation of component installation; W_3R_{23} : Insufficient strength of components supporting; $W_{41}R_{11}$ 、 $W_{41}R_{12}$: Component toppling; $W_{41}R_{21}$: Unreasonable of suspension point; $W_{41}R_{23}$、$W_{41}R_{32}$: Deviation of component position; $W_{41}R_{24}$: Unsecured mechanics; $W_{421}R_{23}$: Node grouting is not in place; $W_{422}R_{23}$: Unstable node; $W_{423}R_{23}$: Uneven pouring; $W_{424}R_{23}$: Improper welding operation; $W_{424}R_{24}$: Short circuit; $W_{425}R_{23}$: Water leakage of joint.

3.5 Fault tree of prefabricated concrete frame structure

The risk factors and risk events is identified according to the coupling of WBS-RBS, and the fault tree analysis of three top events is conducted respectively. An intermediate event and a basic event of the fault tree are matched to the coupling events in Table 1. As shown in Figure 8 to Figure 10.

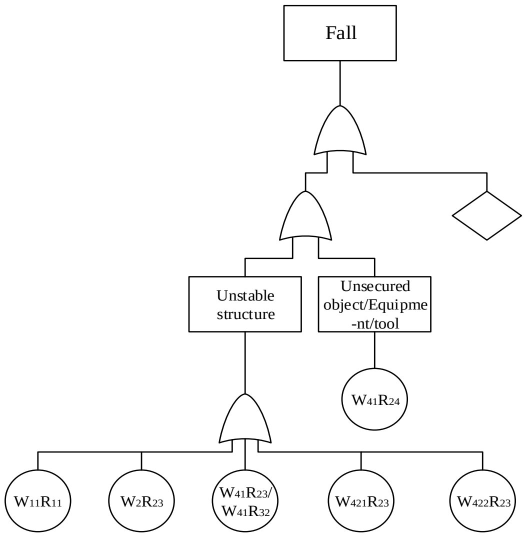

Fig 8. Fault tree of fall

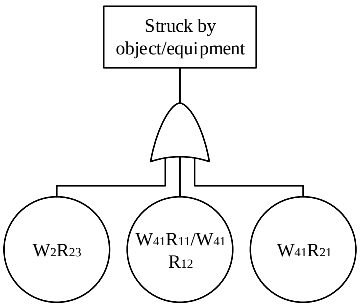

Fig 9. Fault tree of struck by object/equipment

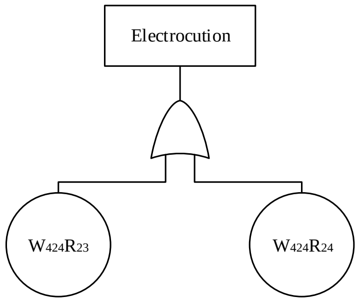

Fig 10. Fault tree of electrocution

3.6 Sensitivity analysis of construction risk factors in prefabricated concrete frame structure

The fault tree of the prefabricated concrete frame structure includes the fault tree of fall, the fault tree of struck by object/equipment and the fault tree of electrocution. As an example, the sensitivity analysis process of the falling fault tree is briefly introduced.

(1) Minimum cut set of falling fault tree

$$\{W_{11}R_{11},\ W_{2}R_{23},\ W_{41}R_{23}/W_{41}R_{32},\ W_{421}R_{23},\ W_{422}R_{23},\ W_{41}R_{24}\}$$

(2) In reference [9], the cause of the crash and the percentage of the total factors in the crash are shown in Figure 11.

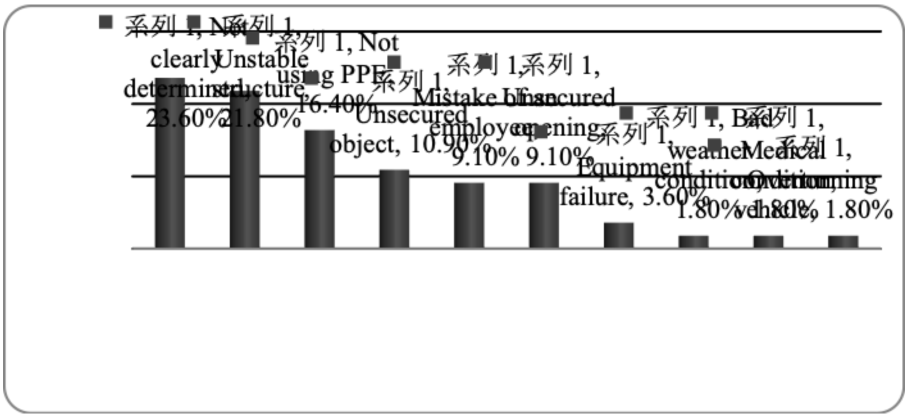

Fig 11. Causes and proportion of falling

According to the intermediate events of falling fault tree, the percentage of the two factors of structural instability and equipment failure in the fall accident are chosen as the probability of occurrence. The fall accident caused by structural instability accounted for 21.8%, the accident of unsecured object/equipment/tool accounted for 10.9%. A safety incident without statistical records is recognized as a small probability event, and its probability ratio is set at an order of magnitude lower than the statistical data, which is recorded as 0.01. It is as follows:

$$P_{W11R11} = 0.01, \quad P_{W2R23} = 0.218, \quad P_{W41R23/W41R32} = 0.218, \quad P_{W421R23} = 0.01,$$
$$P_{W422R23} = 0.01, \quad P_{W41R24} = 0.109$$

Bring the above results into (2):

$$F_S = P(A_1) = 0.471 \approx 0.47$$

The probability of the falling event A1 and the probability of verticality deviation of component installation F_{W2R23} are introduced into (3):

$$\begin{aligned}
Ig(W_2R_{23}) &= \frac{\partial F_s}{\partial F_{W2R23}} \frac{F_{W2R23}}{F_S} = \{1-(P_{W11R11} + P_{W41R23/W41R32} + P_{W421R23} + P_{W422R23} + \\
&P_{W41R24}) + (P_{W11R11}P_{W41R23/W41R32} + P_{W11R11}P_{W421R23} + P_{W11R11}P_{W422R23} + P_{W1R11}P_{W41R24} \\
&+P_{W41R23/W41R32} + P_{W41R23/W41R32}P_{W422R23} + P_{W41R23/W41R32}P_{W41R24} + P_{W421R23}P_{W422R23} \\
&+P_{W421R23}P_{W41R24} + P_{W422R23}P_{W41R24}) - (P_{W11R11}P_{W41R23/W41R32}P_{W421R23} \\
&+P_{W11R11}P_{W41R23/W41R32}P_{W422R23} + P_{W11R11}P_{W41R23/W41R32}P_{W41R24} + P_{W11R11}P_{W421R23}P_{W422R23} \\
&P_{W11R11}P_{W421R23}P_{W41R24} + P_{W11R11}P_{W422R23}P_{W41R24} + P_{W11R11}P_{W421R23}P_{W422R23} + \\
&P_{W11R11}P_{W421R23}P_{W41R24} + P_{W11R11}P_{W422R23}P_{W41R24} + P_{W41R23/W41R32}P_{W421R23}P_{W422R23} + \\
&P_{W41R23/W41R32}P_{W41R23}P_{W41R24} + P_{W41R23/W41R32}P_{W422R23}P_{W41R24} + P_{W421R23}P_{W422R23}P_{W41R24}) \\
&+(P_{W11R11}P_{W41R23/W41R32}P_{W421R23}P_{W422R32} + P_{W11R11}P_{W41R23/W41R32}P_{W421R23} + P_{W41R24} + \\
&P_{W11R11}P_{W41R23/W41R32}P_{W422R23}P_{W41R24} + P_{W11R11}P_{W421R23}P_{W422R23}P_{W41R24} + \\
&P_{W421R23/W41R32}P_{W421R23}P_{W422R23}P_{W41R24}) - (P_{W11R11}P_{W41R23/W41R32}P_{W421R23}P_{W422R23}P_{W41R24})\} \\
&\frac{0.218}{0.471} = 0.3028 \approx 0.303
\end{aligned}$$

The same goes as the follows:

$Ig(W_{11}R_{11}) = 0.011$ $\quad Ig(W_{41}R_{23}/W_{41}R_{32}) = 0.303$ $\quad Ig(W_{421}R_{23}) = 0.011$ $\quad Ig(W_{422}R_{23}) = 0.011$
$Ig(W_{41}R_{24}) = 0.137$

According to the above sensitivity coefficients, the risk factors in the fault tree of fall are sorted, as shown in Table 2.

Table 2. Sensitivity ranking of risk factors for falling

Serial number	**Factor code**	**Sensitivity coefficient**	**Risk factors**
1	W_2R_{23}	0.303	Verticality deviation of component installation
2	$W_{41}R_{23}/W_{42}R_{32}$	0.303	Deviation of component position
3	$W_{41}R_{24}$	0.137	Unsecured mechanics
4	$W_{11}R_{11}$	0.011	Unsecured component
5	$W_{421}R_{23}$	0.011	Node grouting is not in place
6	$W_{422}R_{23}$	0.011	Unstable node

Similarly, the sensitivity coefficients of risk factors in fault tree of struck by object/equipment and the fault tree of electrocution can be obtained, as is shown in Table 3 and Table 4.

Table 3. Sensitivity ranking of risk factors for struck by object/equipment

Serial number	**Factor code**	**Sensitivity coefficient**	**Risk factors**
1	W_3R_{23}	0.327	Insufficient strength of components supporting
2	$W_{41}R_{11}/W_{41}R_{12}$	0.327	Overturning components
3	$W_{41}R_{21}$	0.327	Unreasonable of suspension point

Table 4. Sensitivity ranking of risk factors for electrocution

Serial number	**Factor code**	**Sensitivity coefficient**	**Risk factors**
1	$W_{424}R_{23}$	0.495	Improper welding operation
2	$W_{424}R_{24}$	0.495	Short circuit

The first three items with greater sensitivity coefficients in each accident are selected as the main risk factors. Which are the verticality deviation of component installation, the deviation of component position and the unsecured mechanics are the main reasons for the fall accident. Insufficient strength of components supporting, overturning components and unreasonable of suspension point are the important factors of risk factors for struck by object/equipment. While the electrocution are mostly caused by improper welding operation and short circuit.

4.0 RISK RESPONSE

Falling, struck by object/equipment and electrocution accidents are the main accident types in assembly building construction. According to sensitivity analysis results, effective control measures are established for each risk event.

The deviation of the component verticality and the risk of the component positioning deviation are the most sensitive factors to the fall accident. The component control line must be ejected during construction, and the components are precisely located according to the control line. Secondly, make sure the components remain vertical and stable during lifting and placing, and some metal pads are placed around the components. According to the design elevation in the drawing and the placement position of the components, the verticality deviation of the components are confirmed. The verticality of the components are controlled by theodolite. If there is a little deviation, the components are adjusted by lifting jack and other tools. In the case of falling accident, the risk factors of unsecured mechanics should be controlled. When choosing construction machinery, it should be considered comprehensively according to the environment of the construction site, the height of the building and the lifting of the components. Normally, mobile crane is adopted in the construction of low and multi layer prefabricated concrete building, tower crane is adopted in the construction of high-rise prefabricated concrete building. In order to ensure the usage of mechanical equipment, the on site equipment should be checked and adjusted

In order to prevent struck by object, the factors such as the volume and the focus of the prefabricated component should be considered comprehensively in the design, so as to ensure the rational use of machinery and equipment. Before the lifting of the components, the lifting sequence and number of each component are marked on the components, so as to facilitate the identification for the lifting workers. Meanwhile, the construction unit should carry out safety training and disclosure to the relevant personnel engaged in the lifting operation of prefabricated components. When the components are hoisted, the hanger is reasonably selected to maintain the stability of the prefabricated components, so as to avoid swaying and toppling during the hoisting process. Normally, the vertical of the connecting point in the hook and sling should kept passing through the focus of the transferred components. During the lifting of the components, it should be stable and shouldn’t swing in large amplitude. At the same time, the lifting components should not be suspended for a long time, and measures should be taken to bring the heavy objects down to a safe position. In case of inclement weather such as rain, snow or fog, the hoisting operation should be stopped. For the weight of the prefabricated components and the load during the construction, the support of the components should have enough rigidity and bearing capacity, which can guarantee the stability of the structural system. Only after the components are confirmed stable, can the temporary stabilization measures be removed.

The countermeasures of electrocution are mainly carried out in the following aspects. First of all, in order to make the principle, structure and performance of mechanical are understood by the construction site operators, some regular technical training should be taken for them, so that they can use welding equipment reasonably. When the operators are welding, they must use welding gloves, and the welding gloves required to be dry and reliable. Secondly, the welding equipment should be provided with good isolation protection devices, and the protective cover should be applied at the end of the outer part of the extending box. A device with a latch hole should be concealed in the plane of the insulation plate. Finally, the construction line should be regularly debugged and repaired, so that the line obstacle was excluded during construction.

5.0 CONCLUSION

In order to study the construction risk identification of prefabricated concrete frame structures. The WBS-RBS structure decomposition method and fault tree analysis method are introduced to analyze the risk of assembly type concrete construction, based on the background of prefabricated building development in our country. Then, the risk of prefabricated concrete building on construction stage is analyzed, and specific conclusions are as follows:

(1) Based on the work breakdown structure WBS and the risk decomposition structure RBS, the construction risk WBS-RBS coupling matrix of the prefabricated concrete frame structure can be established, and each risk events related to risk factors of the coupling matrix are determined.

(2) In consideration of the fault tree with falling accident as top event, the sensitivity ranking of risk factors are obtained. The main risk factors are verticality deviation of component installation, deviation of component position and unsecured mechanics. Based on the fault tree with struck by object/equipment accident as top event, the sensitivity ranking of risk factors are obtained. The main risk factors are insufficient strength of components supporting, overturning components and unreasonable of suspension point. In view of the fault tree with electrocution accident as top event, the sensitivity ranking of risk factors are obtained, the main risk factors are improper welding operation and short circuit.

(3) The corresponding measures are made for the three risk accidents, which provided the basis for the rational control of security risks, and also provided a reference for the risk analysis of the other types of prefabricated buildings.

Conflict of Interests

The authors declare no conflict of interest.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support from Social Science Foundation of Sichuan Province of China (No.SC14E074), Scientific Research Project of Sichuan Education Department of China (16SB0064), Young Scholars Development Fund of SWPU (200931010056) and China Scholarship Council (Nos.201808515050).

REFERENCES

Journal Papers

Cai, Y., Xing, Y., Hu, D. (2008). Review of sensitivity analysis. *Journal of Beijing Normal University (Natural Science)*, 1:9-16.

Chen, W., Fu, J., Xiong, F. G., Yang, J. (2016). Grey clustering evaluation model for construction safety of fabricated building project. *China Safety Science Journal*, 11:70-75.

Chen, Z. K., Zhou, Y., Zhang, J. C., Wu, X. (2012). Retroversion and Forecast of Present Research and Application of Precast Concrete Structure. *Earthquake Resistant Engineering and Retrofitting*, 4:1-11.

Danilo, N.D., Tomas, L. (2016). Failure Rate modeling using Fault Tree analysis and Bayesian Network: DEMO pulsed operation Turbine study case. *Fusion Engineering and Design*, 109:613-617.

GMW 2016 Central committee of the communist party of china and the state council on further strengthening the administration of urban planning and construction. Retrieved from http://www.gov.cn/zhengce/2016-02/21/content_5044367.htm .

GOV 2016 Report on production safety accidents in housing and municipal works in 2016. Retrieved from http://finance.sina.com.cn/roll/2017-02-15/doc-ifyamkpy 9499779.shtml.

Jack, S.C., Kathy, D.B., Amie, F. (2001). From raw materials to customers: supply chain management in the service industry. *SAM Advanced Management Journal*, 66(4):14-21.

Li, C. Z., Shen, G. Q., Xu, X. X., Xue, F., Sommer, L., Lou, L. Z. (2017). Schedule risk modeling in prefabrication housing production. *Journal of Cleaner Production*, 153(1):692-706.

Liu, S., Liu, X. Q. (2015). Application of risk management in design and construction process of BIM type residential building. *Liaoning Economy*, 10:61-63.

Maryam, M.F., Seyyed, A.T., Charles, K., Hamed, H. (2017). Safety concerns related to modular/prefabricated building construction. *International Journal for Consumer and Product Safety*, 24(1):10-23.

Mohammed, T., Faisal, K., Zoubida, L. (2016). Availability analysis of safety critical systems using advanced fault tree and stochastic Petri net formalisms. *Journal of Loss Prevention in the Process Industries*, 44:193-203.

Rafele, C., Hillson, D., Grimald, S. (2005). Understanding project risk exposure using the two-dimensional risk breakdown matrix． *2005 PMI Global Congress Proceedings*, 1－8．

Shi, J. G., Lin, S. Z. (2014). Present situation and development prospect of prefabricated concrete structure system. *Wall Materials Innovation & Energy Saving in Buildings*, 1:45-48.

Tang, Y. N. (2015). Research on Estimation of Construction Safety Risks for Prefabricated Housing based on System Dynamics. *Xi`an University of Architecture and Technology*.

Tian, C. Y., Huang, X. K., Li, R., Yin, X. W. (2015). The Research and Application of Prefabricated Concrete Structure. *Construction Quality*, 4:25-30.

Tian, L. (2014). Risk Management Methods and Strategies for Prefabricated Concrete Residence Construction. *East China University of Science and Technology*.

Wang, Y., Liu, B. G., Qi, Y. (2015). Risk Identification and Assessment of Subway Construction Based on Coupling of WBS-RBS and Fault Tree Analysis. *Chinese Journal of Underground Space and Engineering*, 87(S2):404-411.

Wen, M., Wang, H., Wu, F. P. (2015). The Safety Risk Management of Prefabricated Residential Building. *Sichuan Building Materials*, 5:262-264.

Yang, S. (2016). Safety evaluation system of prefabricated building construction. *Shenyang Jianzhu University*.

Zhao, G. J. (2016). The Development Prospects of the Prefabricated Concrete Structure. *Construction Quality*, 7:16-18.

Zhou, H. B., Gao, W. J., Cai, L. B., Zhang, H. (2009). Risk identification and analysis of subway foundation pit by using fault tree analysis method based on WBS-RBS.

Rock and Soil Mechanics, 9:162-166+185.