Application of Analytic Hierarchy Process in Safety Assessment of Reinforced Concrete Structures after Fire Disaster

Jia-Jie Cui, Jun Deng, and Xiao-Da Li

Abstract—**Many factors could affect the safety of reinforced concrete (RC) structures after fire disaster. Quantitative assessment of the safety risk of RC structures after fire remains a major challenge for disaster prevention and mitigation. In this paper, Analytical Hierarchy Process (AHP) was applied to evaluate the safety risk of RC structures after fire qualitatively and quantitatively. Firstly, three aspects-materials, geometries and functions were considered for ten safety evaluation indicators. Afterwards, the fire risk assessment model for RC structures was established and the model was used for a case study. Simultaneously, a workshop after fire damage in Jiangmen city was taken as an example and the AHP was applied to estimate the workshop structural safety risk. It is concluded that the evaluation results obtained by the AHP are in good agreement with the field identification results, which indicates that the AHP is applicable for safety risk assessment of RC structures after fire. The safety evaluation results based on the AHP can provide a reference for structural rehabilitation or demolition after fire, which is significant in fire disaster prevention and reduction.**

Index Terms—**Analytic hierarchy process (AHP), fire, safety risk assessment, RC structures.**

I. Introduction

In the last three decades, with the rapid economic developments and the continuous improvements of urbanization in China, the functions of the buildings have been becoming more and more complicated [1]. In order to meet the requirement of building multi-function, the forms of architectural structure become diversified. Although the multi-functional high-rise buildings meet the needs of people's life and work, the complicated RC structures of the building have some risks. Once a fire has been broken out, the complicated RC structure may delay fire rescue. Under the high temperature for a long time, the strength of concrete and the bonding performance of concrete-steel interface would be sharply declined. As a result, the safety of the RC structure would be threatened. After the fire accident, if the rescue could not be timely, it would cause tremendous loss of people's lives and property. Even worse, the economic development and social stability would also be suffered [2]. Currently, the rescue strategies are lacking of scientific guidance, and sadly, the tragedy occurred due to the collapse of the buildings during the fire rescue. Therefore, in order to ensure the safety of the rescued workers and the success of the rescue process, it is necessary to conduct a risk assessment of the safety of RC structure after fire.

At present stage, fire risk assessment methods include the Fuzzy Comprehensive Evaluation (FCE), the Event Tree Analysis (ETA), the Fault Tree Analysis (FTA) and the Analytic Hierarchy Process (AHP) [3]. FCE is a quantitative evaluation method using fuzzy mathematics to make an overall evaluation of targets that are subjected to various factors [4]. However, it is shown that sometimes over two largest components are equal in FCE, which will lead the results of the evaluation to be failed [5]. ETA is a constructive and modeling way of detecting and analyzing the possibilities of different events with safety features from an initial event, which is shown the sequences of events related to succeed or fail [6]. However, the event tree method is not suitable for assessing the safety risk of RC structure after fire because of the fact that not every element has two states of success and failure. FTA is a deduction that is based on mathematical logic. The probability between the possibility and the cause will be built and analyzed by FTA [7]. However, safety risk assessment of RC structures after fire is a process of evaluating the performance of reinforced concrete and the cause of the fire does not need to be found gradually. Hence, AHP is used to evaluate the safety risk of RC structures after fire in this paper. For the reason that AHP is simple and practical, it is convenient for decision makers to find the optimal solution in many schemes effectively. Consequently, the results of the safety risk assessment of RC structure can be quickly obtained by using AHP [8].

Through a large quantity of reference research, this paper identifies the risk factors affecting the safety of RC structure after fire and the fire safety evaluation index system of RC structure is established. A workshop located in Jiangmen city, Guangdong, which was suffered from fire damage, is taken as an example and AHP is used for assessment analysis [9]. Whether the structure can still be used after being repaired or the structure should be removed is evaluated after the assessment, which is the reference basis for the safety risk assessment of RC structures after fire.

II. Analytic Hierarchy Process (AHP)

The AHP, a new hierarchical method to make effective decisions for analyzing the complicated issues, was proposed by Saaty in the 1970s [10]. Through the establishment of a

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hierarchical model, AHP decomposes the complex problem into several levels and index factors. First of all, the importance of the index factors were compared with each other and the judgment matrix was established. Hereafter, the maximum eigenvalue of the judgment matrix was calculated and the weight of each levels and factors were determined. Finally, the cumulative weight of each indicator was derived and sorted. The advantage of AHP is that it only requires comparisons among different factors separately, and does not require the qualitative comparisons of multiple factors at the same time. Additionally, AHP can transform qualitative comparison into quantitative calculation, which can reduce subjective errors.

In general, the problems analyzed by AHP go through the following steps [11]:

(a) Find out the objectives.

(b) Set up a structural model of hierarchy from the top to the lowest level through the intermediate levels, where the objectives are belonged to the top, the options are belonged to the lowest level and the intermediate levels are in the middle of the model.

(c) Format pair-wise comparison matrices for each level by using the relative scales. For example, if the factor i and the factor j are the same important, the scale is 1. When the factor i is more important than the factor j, the scale is 3. Others are listed in the Table I. Then calculate the maximum eigenvalue, the corresponding vectors of the maximum eigenvalue, the Consistency Index (*CI*) and the consistency ratio (*CR*) of each matrix. The scales in the matrix should be met with Equation (1)

$$a_{ji} = {}^{1}\!/\!_{a_{ij}} \quad (1)$$

(d) Check the consistency of the matrices in the structure model. The consistency ratio is calculated by the Equation (2) [12].

$$CR = CI / RI \quad (2)$$

where *CI* is the consistency index and its numerical size is determined by the Equation (3). *RI* is random index and the value is based on the order of the matrix *n* given in Table II [13].

$$CI = (\lambda - n)/(n-1) \quad (3)$$

where λ is the maximum eigenvalue of the judgment matrix and *n* is the order of the matrix. When the *CR* does not exceed 0.10, the comparison matrix is consistent, or the comparison matrix should not be finished repeating step (c) and step (d) until the *CR* does not exceed 0.10.

(e) Sort the elements and integrate the weight values to reach the decision.

In short, the proceedings of the AHP were given in the Fig.1 [14].

TABLE I: SCALE AND MEANING OF THE MATRIX

	Implication	Scale
1	Factor *i* is as important as factor *j*.	1
2	Factor *i* is more important than factor *j*.	3
3	Factor *i* is obviously important than factor *j*.	5
4	Factor *i* is strongly important than factor *j*.	7
5	Factor *i* is extremely important than factor *j*.	9
6	Compromise the preferences in weights 1,3,5,7 and 9	2,4,6,8

TABLE II: THE AVERAGE CONSISTENCY INDEX OF RI

Order	1	2	3	4	5	6
RI	0.00	0.00	0.52	0.90	1.12	1.24

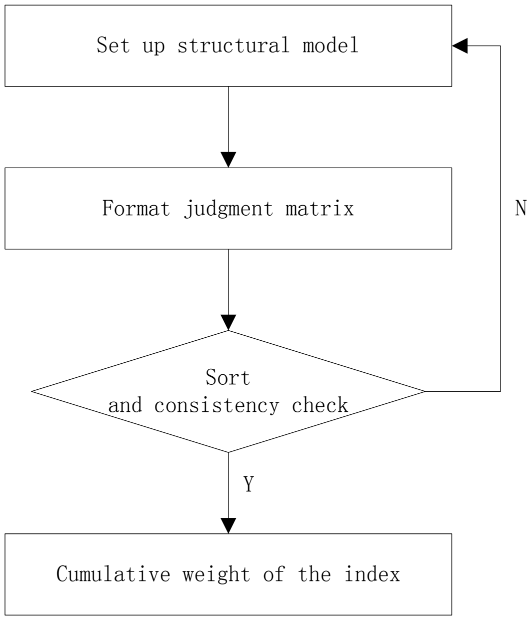

Fig. 1. Proceedings of the AHP [14].

AHP in the bridge risk assessment [15] and prevention of landslide [16] has been successfully applied and obtained good results. Therefore, it is feasible to apply the AHP for the safety risk assessment of RC structures after fire disaster.

For the safety of RC structure after fire, many scholars have studied and discussed. Hui-Qun Yan [17] through the collection of comprehensive literature analysis found that when the temperature of the fire was higher than 400 ^{o}C, the strength of the concrete began to decline. Decarburization of steel would be produced and the strength of the steel decreased when the temperature was over than 600 ^{o}C. Therefore, the temperature exposure, the strength of the steel bar and the strength of the concrete were the important reference indexes to evaluate the safety of the structure after the fire. Hong-Xiu Du [18] investigated the performance of reinforced concrete through a large number of references. The evaluation of concrete damage was put forward, which was the strength of the steel, the strength of the concrete, heating time, fire temperature, fire area and the bonding performance of reinforced concrete. Among them, the high temperature was the main consideration of damage detection and evaluation of concrete after fire. Yuan-Zhe Li [19] found that in a event of fire accident, the thinner the concrete cover, the more easily the heat is transferred to the surface of the steel. He found that different thickness of the concrete cover had an effect on the axial compressive capacity of reinforced concrete specimens after high temperature. Therefore, the thickness of the concrete cover is also one of the important considerations. In CECS252:2009 [20], surface color of concrete, cracks, and falling off were mentioned. It indicated that surface color of concrete, cracks, and falling off were the most important considerations for concrete structure detection and evaluation. According to the change of the surface color, the highest temperature could be reflected. The width of crack and the size of concrete could be determined the safety grade of concrete. However, after the fire, concrete materials were loosened and porous, CECS252: 2009 had mentioned the hammer reaction to determine the grade of the reinforced concrete after fire, which would be brought an extra damage to the concrete and the results may be biased. To sum up, the fire resistance of RC structures could be reflected by many related factors, mainly including strength of concrete, strength of steel, bonding performance, surface color of the concrete, temperature, heating time, thickness of the concrete cover, cracks, and area. The strength of concrete, strength of steel, the bonding performance, and surface color are belonged to the material parameter category. Temperature, heating time, and area are belonged to the functions. Cracks, falling off, and the thickness of concrete cover are belonged to the range of geometries.

In this paper, AHP was used to evaluate the safety risk of RC structures after fire disaster. The complicated multiplicative decision-making problem of RC structures safety after fire was taken as a system. The system is decomposed into materials, functions and geometries. The criteria can be further divided into 10 indexes such as strength of concrete, strength of steel, bonding performance, surface color, temperature, heating time, thickness of the concrete cover, cracks, falling off and area. These ten indexes establish the index evaluation system model, get the judgment matrix by comparison, calculate the weight by the qualitative index fuzzy quantification method, and sort out to get the main risk factors that affect the safety of the RC structure after the fire so as to evaluate quickly and accurately. The safety risk of RC structure was evaluated to put forward specific suggestions and measures for the safety performance of the RC structure after fire, as well as providing a reliable basis for fire fighting and disaster relief.

III. Application of AHP in Safety Assessment for Concrete Structures after Fire Disaster

A. *Project Overview*

A workshop was located in Jiangmen City, which was completed in 2011 and in service from then. The construction area was about 16000 square meters. The workshop structure plane was a rectangle. The height on the first floor of the warehouse was 5.000 meters. The second floor and the third floor were used for the production and their heights were 4.800m and 5.700m. The first floor and the second floor were frame structures. The concrete of columns were made of C30, beams and plates were C25. The third floor was portal frame structures. A fire broke out on the first floor of the workshop in the morning. The fire did not extend to the second floor or the third floor. After the fire was extinguished, the workshop was surveyed, identified and evaluated for safety.

B. *Establishment of Evaluation System*

According to the principle of AHP, an index evaluation system model was established for the RC structure after fire. The problem was the safety risk assessment of RC structures after fire. There are three factors in the criteria and they are materials (A), functions (B), and geometries (C). Materials (A) are strength of concrete (A1), strength of steel (A2), bonding performance (A3), and the surface color of concrete (A4). Temperature (B1), time (B2), and area (B3) are belonging to functions (B). Geometries (C) are cracks (C1), falling off (C2), and the thickness of the concrete cover (C3). In short, the index evaluation system model was shown in Table III.

TABLE III: Index Evaluation Form

Target	Criteria	Index
Safety risk assessment for reinforced concrete after fire	Materials （A）	Strength of concrete（A1）
		Strength of steel（A2）
		Bonding performance（A3）
		Surface color of concrete （A4）
	Functions （B）	Temperature（B1）
		Time（B2）
		Area（B3）
	Geometries （C）	Cracks（C1）
		Falling off（C2）
		Thickness of concrete cover （C3）

C. *Calculating Index Weight*

According to the research of reinforced concrete after fire, Hui-Qun Yan and other researchers [17]-[19] found that during the fire disaster, the time of fire exposure, area of fire exposure and the temperature of fire have an effect on the falling off from the concrete, cracks, the surface color of concrete, burning depth of the concrete, the size of the thickness of the concrete cover, strength and bonding performance. Therefore, by applying the evaluation index system model, the ten factors were shown in Table III combined with CECS252: 2009. The comparison of the ten factors could be solved that every judgment matrix in the numerical scale, maximum features and each judgment matrix calculation with the method of level analysis value. *CI* was calculated by the largest eigenvalue, and according to the order of *RI* numerical judgment matrix, through the comparison of *CI* and *RI*, *CR* was solved that whether the *CR* would be met the requirements or not. If *CR* did not exceed 0.10, the judgment matrix consistency index could be met the requirements or judgment matrix consistency test could not meet the requirements to readjust the judgment matrix internal scale numerical and calculate again, until *CR* was less than 0.10 to meet the inspection requirements so far.

In a judgment matrix, the ratio was 1 when two parameters were the same. For the comparison between two different parameters, if the former was more important than the latter, the ratio was a positive integer. If the former was less important than the latter, the ratio was the reciprocal of the positive integer. Take Table IV as an example, the ratio of material (A) and material (A) was 1 where functions (B) and geometries (C) were the same. And the contrast materials (A) and functions (B), functions (B) was more important than the materials (A) and so does geometries (C), so A/B=1/2, B/A=2/1. A/C=1/2, C/A=2/1. The scale values of each row of parameters A, B, and C were multiplied, and the results were rooted. The results were normalized and the weight corresponding to each parameter was obtained. Similarly, in the materials (A), A1/A2=1/1, A1/A3=1/2, A1/A4=2/1, A2/A3=1/2, A2/A4=2/1, A3/A4=3/1, A2/A1=1/1, A3/A1=2/1, A4/A1=1/2, A3/A2=2/1, A4/A2=1/2, and A4/A3=1/3. In the functions (B), B1/B2=3/1, B1/B3=3/1, B2/B3=1/1, B2/B1=1/3, B3/B1=1/3, and B3/B2=1/1. In the geometries (C), C1/C2=1/3, C1/C3=2/1, C2/C3=5/1, C2/C1=3/1, C3/C1=1/2, and C3/C2=1/5. The values of each scale and the weight after normalization were shown from Table IV to Table VII.

According to the results obtained by the calculation of the judgment matrix above, *CR* of the matrices were 0.0462, 0.0168, 0.0000, and 0.0063, which met the requirements.

TABLE IV: JUDGMENT MATRIX OF PARAMETERS

	A	B	C	weight
A	1	1/2	1/2	0.1958
B	2	1	1/2	0.3108
C	2	2	1	0.4934

λ_{max}=3.0536，CR=0.0462＜0.1

TABLE V: JUDGMENT MATRIX OF MATERIALS

A	A1	A2	A3	A4	weight
A1	1	1	1/2	2	0.2008
A2	1	1	1/2	2	0.2222
A3	2	2	1	3	0.4577
A4	1/2	1/2	1/3	1	0.1194

λ_{max}=4.0457，CR=0.0168＜0.1

TABLE VI: JUDGMENT MATRIX OF FUNCTIONS

B	B1	B2	B3	weight
B1	1	3	3	0.6000
B2	1/3	1	1	0.2000
B3	1/3	1	1	0.2000

λ_{max}=3.0000，CR=0.0000＜0.1

TABLE VII: JUDGMENT MATRIX OF GEOMERTIES

C	C1	C2	C3	weight
C1	1	1/3	2	0.2297
C2	3	1	5	0.6483
C3	1/2	1/5	1	0.1220

λ_{max}=3.0037，CR=0.0063＜0.1

D. Results and Discussions

The cumulative weight of various factors affecting the safety of RC structures after a fire was listed in Table VIII. When the weight of materials (A) was the highest, the structure was safe because the time of fire was short, the temperature of fire was low and the area of fire was small enough that cracks and falling off had little existence. The structure was needed to be minor repaired when the weight of functions (B) was the highest and the weight of materials (A) was higher than the weight of geometries (C), or the structure was needed to be overhaul when the weight of functions (B) was the highest and the weight of geometries (C) was higher than the weight of materials (A). When the weight of geometries (C) was the highest, it indicated that the damage of the structure was so severe that the structure was in danger and all the people needed to stay away. According to the calculation results of Table VIII, it can be seen that in the criteria, the weight of geometries (C) (0.4934) was the highest. The weight of the functions (B) was 0.3108, which was higher than the weight of the materials (A)(0.1958). In the index layer accumulation weight sorting, the weight of the concrete falling off was the largest. The concrete was fallen off and the reinforcement was exposed in the high temperature, which resulted in the decomposition of the internal heat of the concrete and the decarburization of the steel bar. The strength decreases, resulting in the decrease of the bearing capacity of the structure, so the structure needs to be demolished. The detection results of the identification for the workshop fire show that the highest temperature reached 800 degrees with duration of 9.5 hours and the fire exposure area reached 3500 square meters. The surface of the concrete in the disaster area turned yellow or gray. Some of the concrete members with serious shedding were evaluated as III or IV components. The structural dismantling and replacement should be done, which was consistent with the result of risk assessment by AHP. Therefore, the application of AHP to the safety risk assessment of reinforced concrete structure after fire was feasible, and the result of evaluation was reliable for providing emergency treatment plan of reinforced concrete structure after fire.

TABLE VIII: SUMMARY OF CALCULATION RESULTS OF RISK ASSESSMENT SYSTEM OF REINFORCED CONCRETE STRUCTURES AFTER FIRE

Target	Criteria	Weight	Index	Weight	Cumulative weight
Safety risk assessment for reinforced concrete after fire	Materials（A）	0.1958	Strength of steel bars（A1）	0.2008	0.0431
			Strength of concrete（A2）	0.2222	0.0447
			Surface color of concrete（A3）	0.4577	0.0795
			Bonding performance（A4）	0.1194	0.0232
	Functions（B）	0.3108	Temperature（B1）	0.6000	0.1864
			Time（B2）	0.2000	0.0622

		Area （B3）	0.2000	0.0622
Geometries （C）	0.4934	Cracks （C1）	0.2297	0.1131
		Falling off （C2）	0.6483	0.3054
		Thickness of concrete cover （C3）	0.1220	0.0577

IV. Conclusion

In this paper, AHP was used to establish index system model and judgment matrix for evaluating the safety risk of RC structure after fire.

(a) Based on the national standards and a large number of literature research, the index factors affecting the safety of reinforced concrete structures after fire could be divided into three categories including a total of 10 index factors. Combined with the weight of each index project, the safety risk analysis model of RC structure could be established after the fire damage.

(b) According to a fire in the workshop of Jiangmen city, AHP was applied to evaluate the workshop structural safety risk. The evaluation results obtained by AHP were in good agreement with the field identification results, which indicated that AHP was applicable for safety risk assessment of RC structures after fire.

(c) The evaluation results of the RC structures after fire based on AHP could provide a reference for rehabilitation or demolition, which is significant for fire disaster prevention and reduction.

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