Comprehensive safety assessment for CFST tied arch bridge subjected to explosion

Peng Sun¹², Xiaomeng Hou¹*

¹ Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education, Harbin Institute of Technology, Harbin, 150090, China
² School of Highway, Chang'an University, Xi'an, 710064, China
* Corresponding author’s e-mail: houxiaomeng@gmail.com

Abstract. Accidental vehicle explosion and car bomb blast causes certain damage to bridge structure, while studies on safety assessment for bridge structures subjected to blast are limited, especially for the concrete filled steel tube(CFST) tied arch bridge(tied arch bridge in short). This study developed a safety assessment index system for CFST tied arch bridge under explosion by the modified analytic hierarchy process(AHP) model based on catastrophe theory. The Jinta bridge was used as a demonstration case for this study and the dynamic responses of tied arch bridge under explosion loading was simulated by numerical simulations. The results show that the proposed system can reflects the safety condition of the tied arch bridge after explosion. The evaluation system presented in this study can serve as an approach for the safety assessment of tied arch bridge and provide the basis for engineering decision-making of bridge structures after explosion accident.

1. Introduction

After vehicle blast accidents and vehicle bomb terrorist attacks, a large number of damaged locations on the bridge are hard to detect, the reduction of bearing capacity and stiffness endangers the safety of bridge. It is imperative to establish a safety assessment system of bridge structure under explosion, and traffic control and engineering decisions should be taken according to the evaluation results to avoid secondary accidents[1].

Established scientific methods for developing bridge structure safety assessment include AHP, Grey Theory(GT), and Fuzzy Comprehensive Evaluation(FCE) methods. The research on the safety assessment of explosion is mainly concentrated in the fields of coal mines, tunnels and buildings. Yuan et al. [2] established the evaluation index system for the safety assessment of highway bridge construction by integrating network analysis method(ANP) and FCE method. However, these improved methods are complicated and difficult to handle weights correctly. Accordingly, the current study utilize catastrophe theory model to address subjectivity in the weighting assignment of factor parameters. To the best of our knowledge, the application of this theory to tied arch bridge safety assessment under blast loading has not yet been investigated.

The current research proposes a safety assessment system for tied arch bridge under explosion based on an AHP-based catastrophe theory model. The proposed safety assessment system is illustrated through a CFST tied arch bridge in Jiangsu, China.
2. Improvement of AHP method based on catastrophe theory

The AHP-based catastrophe model evaluate the dependency of state variable on control parameters through catastrophe membership function instead of assigning weights by expert judgment[3]. The progress of optimized AHP method based on catastrophe theory is shown in Figure 1.

It should be noted that when exploring the factors affecting the problem in the AHP method, the main factors should not be overlooked to cause the decision-making inaccuracy. Using the normalized formula to quantify the recursive operation of the system, the total catastrophe membership function value of the system characterizing the state of the system can be obtained. The catastrophe fuzzy membership functions are listed in Table 1[3].

![Diagram of AHP-based catastrophe theory model](image)

Figure 1. The process of AHP-based catastrophe theory model.

According to the nature of practical problems, two different criteria can be adopted in the practical application of catastrophe theory-based evaluation methods: 1) non-complementary criterion: the minimum value of normalized control parameters represents the state of system; 2) complementary criterion: the mean value of control parameters shows the state of system[5].

3. Comprehensive safety assessment of tied arch bridge under explosion

3.1 Safety evaluation index system

The structural safety is mainly determined by comparing the bearing capacity of the bridge with the load effect. The bearing capacity can be reflected by the peak strain and stress at critical section of structural members under blast loading and the damage situation of bridge structure after explosion[1]. The magnitude of the damage caused by the explosion is mainly influenced by traffic flow, vehicle size, the infrastructure density and distance from the explosion location. In addition, the explosion damage capability is also affected by explosion-proof system and emergency facilities[5]. This paper utilizes the viewpoint of safety system engineering to conduct an overall investigation and analysis,
and the multi-level safety assessment index system based on catastrophe theory is established as shown in Figure 2.

![Figure 2. The methodological flowchart of safety assessment of tied arch bridge established on AHP-based catastrophe theory model.](image)

3.2 Normalization of data layers

On account of different layers having different units of measurement, all of the parameters and index should be normalized. The material strength is obviously improved under the action of explosion, while the critical strain and ultimate strain of concrete and steel are basically unchanged under high strain rate. For the members of bridge structure within the scope of explosion damage, the safety index of concrete ($\psi$) and steel ($\theta$) is defined based on the strain of the material and the principal strain of material according to the second strength theory:

$$\psi = \frac{\sigma_{\psi}}{\sigma_{\psi}} - 1, \quad \theta = \frac{\sigma_{\theta}}{\sigma_{\theta}} - 1$$

Where $\sigma_{\psi}$ is the principal stress of concrete at the control section of bridge structure under explosion; $\sigma_{\theta}$ is von-mises stress of steel; $\sigma_{\psi}$ is the strength of concrete under high strain rate, $f_c$ and $R_{un}$ is yield strain of steel. For the members of bridge outside the explosion damage range, the safety index of concrete($S_c$) is defined based on the strength under high strain rate and the principal stress of concrete according to the first strength theory; the safety index of steel($S_s$) is based on the yield strength under high strain rate and the Mises stress of steel according to the fourth strength theory[6]. The normalized function of carrying capacity can be expressed as:

$$S = 1 - \frac{\sigma_{\text{unis}}}{R_{un}}$$

Where $\sigma_{\text{unis}}$ is the principal stress of concrete at the control section of bridge structure under explosion; $\sigma_{\text{unis}}$ is von-mises stress of steel; $\sigma_{\text{unis}}$ is the strength of concrete under high strain rate, $f_c$ and
$f_c$ is the dynamic tensile strength and compressive strength of concrete, respectively. $\sigma_y$ is the yield strength of steel under high strain rate.

The normalization of each factor in damage situation is mainly determined by the damage ratio of each member of tied arch bridge after explosion, the maximum crack width, the corrosion rate of main bars and the test data of actual bridge, etc., and the score is determined by “Standards for technical condition evaluation of highway bridge”[4].

The factor index of facility conditions and environmental conditions obtained from literature[6], each factor can be normalized according to Table 2.

### Table 2. Factor index of environmental and facilities condition for tied arch bridge.

| Layer | Description and the range of factor | Over bad | Very bad | Bad | General | Good | Very good | Perfect |
|-------|-------------------------------------|----------|----------|-----|---------|------|-----------|---------|
| B_3   | C_{10}                              | [0,0.2]  | (0.2,0.4] | (0.4,0.6] | (0.6,0.8] | (0.8,0.9] | (0.9,0.95] | >0.95   |
|       | C_{11}(\text{}/m^2)                 | ≥90      | [85,90)  | [75,85)  | [55,75)  | [45,55] | [30,45]  | [0,30] |
| B_4   | C_{12}(\text{}/m^2)                 | [0,0.01] | (0.01,0.05] | (0.05,0.1] | (0.1,0.16] | (0.16,0.18] | (0.18,0.2] | >0.2    |
|       | C_{13}                              | [0,0.2]  | (0.2,0.4] | (0.4,0.6] | (0.6,0.8] | (0.8,0.9] | (0.9,0.95] | >0.95   |

### 3.3 Safety assessment rank

The safety rating of the tied arch bridge under explosion is determined in reference to the technical condition evaluation of bridge in “standards for technical condition evaluation of highway bridge”, “code for maintenance of highway bridges and culverts” and “technical code of maintenance for city bridge”. In this paper, the safety state of the tied arch bridge under explosion is divided into five ranks in reference to the advantages of the above code, as listed in Table 3.

### Table 3. Standard of safety level for tied arch bridge.

| Rank of catastrophe membership function value | ≥88 | [60,88) | [40,60) | [0.2,0.4) | <0.2 |
|---------------------------------------------|-----|--------|--------|-----------|------|
| Description                                 | Perfect | Good | Eligible | Unqualified | Danger |
| Rank                                        | I | II | III | IV | V |

### 4. Case study

Jinta bridge is located in Jintan, Jiangsu, China, which is a through concrete filled steel tubular tied arch bridge. Because of no report of car blast accident happened on the bridge, this paper utilizes finite element modeling to simulate the explosion of the mini car (explosive weight 50 kg TNT, distance 0.5 m) on the bridge[6]. The explosion position is at the center of the bridge above the deck, the dynamic response of key sections of the members of the tied arch bridge under explosion is shown in Table 4. For the components outside the explosion range, it is assumed the strain rate has no effect on the strength of the steel and concrete in consideration of safety. Since the explosion occurred on the bridge deck, the damage of substructure was not considered[6].

### Table 4. Normalized value of factor for bearing capacity of arch tied bridge under explosion.

| Members of bridge | Position                  | Stress(MPa) or strain | Normalized Value |
|-------------------|---------------------------|-----------------------|-----------------|
| Steel tube        | Upper edge of steel tube  | 92.24                 | 0.733           |
|                   | Lower edge of steel tube  | 88.30                 | 0.744           |
| Arch rib          | Concrete in upper tube    | -12.60                | 0.315           |
|                   | Concrete in lower tube    | 0.52                  | 0.696           |
| Concrete member   | Joint of hanger and tied beam | -13.59                | 0.412           |
According to the safety evaluation process of the tied arch bridge under the explosion established in Figure 2, the factors index of each control parameter are normalized respectively, then the weight of each layer is determined based on the catastrophe theory, finally the total catastrophe membership function value is obtained. The safety assessment results of tied arch bridge are listed in Table 5, and the order of the parameters and indexes at each level are the primary and secondary relationship between them.

Table 5. Safety assessment results of tied arch bridge subjected to explosion.

| Control parameters | Normalized Value of factor index | Catastrophe membership function | Priority based on complementary principle | Catastrophe membership function | Total catastrophe membership function value |
|--------------------|---------------------------------|---------------------------------|-------------------------------------------|---------------------------------|---------------------------------------------|
|                    | C1                              | 0.98                            | 0.99                                      | 0.69                            | 0.83                                       |
|                    | C2                              | 0.32                            | 0.68                                      |                                 |                                             |
| B1                 | C3                              | 0.81                            | 0.95                                      | 0.69                            | 0.83                                       |
|                    | C4                              | 0.41                            | 0.84                                      |                                 |                                             |
|                    | C5                              | 0.00                            | 0.00                                      |                                 |                                             |
|                    | C6                              | 0.98                            | 0.99                                      |                                 |                                             |
| B2                 | C7                              | 0.90                            | 0.97                                      | 0.94                            | 0.98                                       |
|                    | C8                              | 0.45                            | 0.82                                      | 0.94                            | 0.98                                       |
|                    | C9                              | 0.85                            | 0.97                                      |                                 |                                             |
| B3                 | C10                             | 0.63                            | 0.79                                      | 0.79                            | 0.94                                       |
|                    | C11                             | 0.83                            | 0.94                                      | 0.79                            | 0.94                                       |
|                    | C12                             | 0.78                            | 0.88                                      |                                 |                                             |
| B4                 | C13                             | 0.85                            | 0.95                                      | 0.88                            | 0.97                                       |

The total catastrophe membership function value of the tied arch bridge subjected to explosion is 0.83, and the assessment result of safety rank is II. Through the safety evaluation system in this paper, the total catastrophe membership function value of tied arch bridge in a period of time can be calculated, and the safety state of tied arch bridge can be judged by analyzing the law of the data. It is possible to calculate the total catastrophe membership function value in several years to predict the safety state of tied arch bridge.

5. Conclusion

In this study a safety assessment system for the tied arch bridge under the explosion was established based on AHP-based catastrophe theory model. The main conclusions of this study are summarized below:

1. The reasonable quantification methods for each factor index were proposed. Based on the dynamic response, traffic conditions and damage of tied arch bridge, normalization method for each factor index is presented. After dividing the hierarchy rationally, the catastrophe membership function value of each layer was determined and the safety rank of the tied arch bridge was obtained.

2. The impact of the explosion risk source and environment conditions on the safety status of the bridge under explosion was considered in the proposed safety assessment system. The evaluation
results not only reflect the safety of the bridge under explosion, but also include the safety of the surrounding structure, pedestrians and vehicles.

(3) This study introduced the AHP-based catastrophe theory model, which efficiently handled the weights and ratings of the factors during safety evaluation, and the objectivity of the safety assessment results was improved.

References

[1] Uzgider, E., Aydogan, M., Caglayan, O., Ozakgul, K., Tezer, O. (2009) Performance of a Tied-Arch Reinforced Concrete Railway Bridge: Rating, Safety Assessment, and Bond Length Evaluation. Journal of performance of constructed facilities, 23(5): 366-371.

[2] Yuan, J.B., Cui, G., Fu, Q.S., et al. (2014) Study on safety risk assessment of highway bridge construction based on the analytic network process. Science&Technology Progress and Policy, 31(11): 96-100. (In Chinese)

[3] Gong, Z.M., Zhou, X.Q., Bo, Z. (2008) The application of Catastrophe Theory in the safety assessment of construction. In: 3rd International Symposium on Modern Mining and Safety Technology. Fuxin. pp. 279-282.

[4] JTG/T H21-2011. (2011) Standards for technical condition evaluation of highway bridges. China Communications Press, Beijing.

[5] Luo, T.Y., Duan, L.X., Wang, J.J., Liu, N., Wu, F. (2016) Analysis and safety assessment of fire and explosion accidents of gas stations based on the catastrophe theory. Safety and enviromental engineering, 23(4): 104-108.

[6] Zhu, J.S., Xing, Y. (2015) Dynamic response and damage process analysis of urban bridge subjected to blast load. Journal of Tianjin University, 48(6): 510-519.