FUZZY ESTIMATION METHOD ON THE SAFETY PERFORMANCE OF EXISTIONG CURTAIN WALLS

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ABSTRACT:

The overall health condition of architectural curtain wall was contributed by the health condition of its various components. Therefore, the relationships between the partial and the overall health conditions of architectural curtain wall were founded based on the fuzzy theory and this method made the estimation even more numerical, objective and convenient. Then the security estimation of curtain wall was studied. An evaluation method on the seismic performance of curtain walls was put forward and verified. It is estimated to be a useful measure for the technicians and researchers on the qualification assessments of architectural curtain walls.

KEYWORDS: architectural curtain wall, security estimation, fuzzy theory, seismic performance

1. INTRODUCTION

China has been a country who produced and constructed the most curtain walls each year nowadays. But at the same time, the safety problem attracted many people's eyes too [1]. Curtain walls were installed on the main structures and took enveloping roles to provide comfortable environment for users. It's necessary to found methods to evaluate the security conditions of the existing curtain walls and guide the engineers in practice.

The security performance estimation of the existing curtain walls includes basic security performance estimation (security performance in natural conditions), seismic performance security estimation (security performance during earthquake action), wind resistance performance security estimation (security estimation under strong wind action), high temperature resistance security estimation (security estimation under temperature deference) and synthetically security evaluation and so on.

The primary content of this paper are basic security evaluation and seismic performance security evaluation of the existing curtain wall. Fuzzy theory [2]-[3] and the current codes [4]-[5] are both referenced in the security evaluation of the existing curtain wall.

2. SECURITY EVALUATION OF THE EXISTING CURTAIN WALL ON FUZZY THEORY

The curtain wall system usually consists of the panel, support system, adhesives and anchoring elements. The security systemic evaluation of the existing curtain wall was classified as the curtain wall system, curtain wall unit and curtain wall members. The evaluation has three steps corresponding to the three classes as above mentioned.

At first, the curtain wall member evaluation. The security risk has two types, one is hazard member, and the other is unhazard member, which refer as remark set $U = \{T_d, F_d\}$. The hazard member is the one whose bearing capacity and deformation could not satisfied the requirements. As for a certain kind of member, several factors were checked and then the factor subset comes into being. Steel poles or beams, for example, their bearing capacity, connection strength, deformation capacity and details should be considered. Member risk evaluation is not the result of the fuzzy operation of the fuzzy matrix of the fuzzy subset (weight set) of the remark matrix, but the hazard sign or hazard member which was listed out once the hazard point or hazard member occurred. The member is unhazard member if there is no hazard point in it.

Many risk phenomenon could not be divided into numerous factors, and different factors may affect each other, and some factors is not so clear at present and it is very difficult to clarify their effect, therefore, the above-mentioned evaluation method was adopted. The method access the member type according the series of the hazard phenomenon sign, ignoring the factor subset of the member type. The membership degree of the hazard point (HP) is 1 once it satisfies the hazard sign, otherwise it is 0. In the process of the hazard evaluation, all hazard phenomenons have the same weight factors.

The curtain wall members such as panel, support system, adhesives and anchoring elements, they have one factor p—the percentage of the hazard members in each factor subset respectively, and p is the weighted average value of all the member's hazard points. There are four grades including a, b, c, d of the members and they consist set *U={a, b, c, d}*. The descriptions on four grades are Grade a: no HP, Grade b: HP, Grade c: Hazard in local area, Grade d: total hazard.

According the percentage *p* of the hazard members and their corresponding membership function, the evaluation result of kinds of members could be acquired as fuzzy vectors $B_i\{\mu_{pi},\mu_{si},\mu_{ci},\mu_{ai}\}$, where *i* denote the panel, support system, adhesives and anchoring members respectively. The four kinds of members of the curtain wall above form the security evaluation factor set of the curtain wall. There are four evaluation grades including A, B, C, D, and the evaluation set *U={A,B,C,D}*. The description of the four grades is illustrated in table 2.1.

Table 2.1 Safety level classification of the curtain wall members [1]

Grade	Security Performance
A	Intact in a whole and no obvious damage and all the members are safe.
B	No obvious damage in a whole and no obvious crack of the panel and the coat of the coating glass do not peeling or fading, the panel strength satisfies design requirements, structural adhesives is aging in a certain extent but it satisfies the requirement, support system rust contingently.
C	There is little damage in a whole, no evident crack of the panel, the structural adhesives aged and the strength reduced, some members of the support system rust.
D	There are obvious damages in a whole and evident crack of the panel. The structural adhesives aged seriously. Most members of the support system rust.

The evaluation vector result of the four parts forms a evaluation matrix: $\underset{\sim}{R}=\left[\underset{\sim}{B}_p, \underset{\sim}{B}_s\ \underset{\sim}{B}_c, \underset{\sim}{B}_a\right]^T$. In order to decide the importance degree of each factor, weight factor set $\underset{\sim}{A}$ was introduced. Evaluation result could be got after compound operation of the fuzzy matrix. $\underset{\sim}{B}=\underset{\sim}{A}*\underset{\sim}{R}$, and $\underset{\sim}{B}=\{\mu_A,\mu_B,\mu_C,\mu_D\}$, each factor in the matrix denotes the membership degree of the curtain wall security grade.

As for fuzzy vector $\underset{\sim}{B}$ get from synthetically evaluation, conclusion on the security performance of the whole curtain wall could be drawn utilizing proper analysis.

3. ACCELERATION INDEX DISCUSSION [6]

3.1. General Principles

Curtain wall risk appraisal based on the HP evaluation, the member is hazard once the hazard phenomenon appeared. For convenient, HP was described in mathematical method or in language, therefore, this demand the on-site engineer's judgment according to the observation and investigation results. In order to get the law of the curtain wall health condition and forecast its durability in the future, the serviceability, history and the environment should be consulted, thereby, on-site investigation and test in laboratory is an important step.

Member level is the lowest one in the synthetically evaluation. In this step, a typical curtain wall unit should be selected, and then each detail members should be investigated. The member classification should approve the rules as bellow.

1） In the curtain wall unit, a single pole, single beam and a single panel.
2） Structural adhesive of the hidden frame curtain wall.
3） A single cable-stayed frame in cable-stayed frame point support glass curtain wall.
4） Steel overlap connector in point-supported curtain wall.

5） Anchoring member

Hazard evaluation would be discussed as follows.

3.2. Curtain Wall Panel

Curtain wall panel bears the wind force and the temperature difference action directly; it takes the important position in the whole system. The hazard phenomenon was listed as below.

1） Bearing capacity is not enough.
2） Deflection capacity is not enough.
3） Cracks appeared in the panel.
4） Metal panel lose its stability.
5） Many cracks appeared in concrete panel.

3.3 Support System

Support system transfers the force from the panel to the main structure which the curtain wall installed on. The hazard phenomenon was listed as below.

1） Bearing capacity of the beams is not enough.
2） Bearing capacity of the poles is not enough.
3） Great deformation of the curtain wall frame.
4） The frame is not suit to the panel.

3.4 Adhesives

Adhesive is the characteristic of the curtain wall structure compared to other structures. It has two kinds, one is structural sealing adhesive which has sealing function and contribute to the comfortable indoor environment the other is structural which has the bearing ability. Thus, the hazard evaluation of the two kinds should be differentiated. The possible hazard phenomenon was listed as below.

1） Bearing capacity is not enough or even lost the capacity.
2） Sealing adhesive aged seriously.
3） Structural adhesive aged and its bearing capacity reduced.
4） Sealing adhesive aged.
5） Structural adhesive peeling and fading.

3.5 Anchoring Members

Anchoring members consists of chemical dowel, screw, bolt and overlap connector, they have the anchoring ability and once they lose their function the panel might crack or even fall down. The possible hazard phenomenon was listed as below.

1） Metal claw damage or bearing capacity is not enough.
2） Not enough bearing capacity of the chemical dowel.
3） Bolt or screw has not enough bearing capacity.
4） Rustiness appeared seriously and the bearing capacity reduced.

4. BASIC SECURITY PERFORMANCE EVALUATION OF THE CURTAIN WALL

4.1. General Rules

Distinguish the hazard members and the unhazard members according the risk evaluation method, then the *p* was work out with equation (4.1) below.

$$p_i = n_d / n \times 100\% \tag{4.1}$$

Where, p_i = hazard members percentage of the curtain wall, *i*= parts of the curtain wall, n_d = number of hazard members, n = number of total members.

Grade a, b, c, d was decided by the percentage of the HP. Suppose *p*=0%, for grade a, *p*=10% for grade b, *p*=40% for grade c, *p*=100% for grade d. In the mid space between each grade, linear function was adopted. Membership function of grade a, b, c and d are supposed as bellow (hidden frame glass curtain wall).

$$\mu_a = \begin{cases} 1, (p = 0\%) \\ 0, (0\% < p \le 100\%) \end{cases} \tag{4.2}$$

$$\mu_b = \begin{cases} 1, (p \le 10\%) \\ \dfrac{40\% - p}{30\%}, (10\% < p \le 40\%) \\ 0, (40\% < p \le 100\%) \end{cases} \tag{4.3}$$

$$\mu_c = \begin{cases} 0, (p \le 10\%) \\ \dfrac{p - 10\%}{30\%}, (10\% < p \le 40\%) \\ \dfrac{100\% - p}{60\%}, (40\% < p \le 100\%) \end{cases} \tag{4.4}$$

$$\mu_d = \begin{cases} 0, (p \le 40\%) \\ \dfrac{p - 40\%}{60\%}, (40\% < p \le 100\%) \end{cases} \tag{4.5}$$

Transit the acquired percentage p into equation (4.2) ~ (4.5), the membership degree to the grade a, b, c, d of curtain wall parts such as panel, support system, adhesive and anchoring members could be got as below:

$$\underset{\sim}{B}_s = \{\mu_{as}, \mu_{bs}, \mu_{cs}, \mu_{ds}\} \quad \underset{\sim}{B}_p = \{\mu_{ap}, \mu_{bp}, \mu_{cp}, \mu_{dp}\} \quad \underset{\sim}{B}_c = \{\mu_{ac}, \mu_{bc}, \mu_{cc}, \mu_{dc}\} \quad \underset{\sim}{B}_a = \{\mu_{aa}, \mu_{ba}, \mu_{ca}, \mu_{da}\}$$

Therefore, the evaluation matrix $\underset{\sim}{R}$ is $\underset{\sim}{R} = \begin{bmatrix} \underset{\sim}{B}_p \\ \underset{\sim}{B}_s \\ \underset{\sim}{B}_c \\ \underset{\sim}{B}_a \end{bmatrix} = \begin{bmatrix} \mu_{as}, \mu_{bs}, \mu_{cs}, \mu_{ds} \\ \mu_{ap}, \mu_{bp}, \mu_{cp}, \mu_{dp} \\ \mu_{ac}, \mu_{bc}, \mu_{cc}, \mu_{dc} \\ \mu_{aa}, \mu_{ba}, \mu_{ca}, \mu_{da} \end{bmatrix}$ (4.6)

Considering the importance of each part of the curtain wall, the weight factor vector $\underset{\sim}{A}$ should be set subjectively according to the experience. Different types of the curtain wall have different $\underset{\sim}{A}$, refer to table 4.1. If $\underset{\sim}{A}=[0.2,0.3,0.2,0.3]^T$, after compound operation of the fuzzy matrix, the evaluation result is

$$\underset{\sim}{B} = \underset{\sim}{A} * \underset{\sim}{R} = \{\mu_A, \mu_B, \mu_C, \mu_D\} \tag{4.7}$$

Where, μ_A = membership degree to grade A, μ_B = membership degree to grade B, μ_C = membership degree to grade C, μ_D =membership degree to grade D, as illustrated in equation (4.8).

Table 4.1 Basic safety weight vector values of curtain wall

Curtain wall type		Weight vector A^T
Glass curtain wall	Framed glass curtain wall	[0.2，0.4，0，0.4]
	Hidden framed glass curtain wall	[0.2，0.3，0.2，0.3]
	Partial Hidden framed glass curtain wall	[0.2，0.3，0.1，0.4]
Steel plate or aluminum panel curtain wall		[0.1，0.4，0，0.5]
Concrete panel, porcelain enamel panel or stone curtain wall		[0.2，0.4，0，0.4]

Calculator M（$\cap$，$\cup$）was applied in equation (4.7)

$$\begin{cases} \mu_A = \max[\min(0.2, \mu_{ap}), \min(0.3, \mu_{as}), \min(0.2, \mu_{ac}), \min(0.3, \mu_{aa})] \\ \mu_B = \max[\min(0.2, \mu_{bp}), \min(0.3, \mu_{bs}), \min(0.2, \mu_{bc}), \min(0.3, \mu_{ba})] \\ \mu_C = \max[\min(0.2, \mu_{cp}), \min(0.3, \mu_{cs}), \min(0.2, \mu_{cc}), \min(0.3, \mu_{ca})] \\ \mu_D = \max[\min(0.2, \mu_{dp}), \min(0.3, \mu_{ds}), \min(0.2, \mu_{dc}), \min(0.3, \mu_{da})] \end{cases} \tag{4.8}$$

The membership grade was acquired on the maximum membership law (MM), thus, if $\mu_A = \max(\mu_A, \mu_B, \mu_C, \mu_D)$, the curtain wall is grade A, if $\mu_B = \max(\mu_A, \mu_B, \mu_C, \mu_D)$, the curtain wall is grade B, if $\mu_C = \max(\mu_A, \mu_B, \mu_C, \mu_D)$, the curtain wall is grade C, if $\mu_D = \max(\mu_A, \mu_B, \mu_C, \mu_D)$, the curtain wall is grade D. If two or more membership degree above is equal from each other, the lower security grade should be selected.

4.2. Example 1

There is hidden framed glass curtain wall. The hazard member percentage is 10% for panel, 20% support system, 30% for adhesive and 0% for anchoring members after investigation. Please estimate the security performance of the curtain wall.

Solve, transit p=[10%,20%,30%,0%] into equation (4.2) ~(4.5), $$\underset{\sim}{R} = \begin{bmatrix} \underset{\sim}{B}_p \\ \underset{\sim}{B}_s \\ \underset{\sim}{B}_c \\ \underset{\sim}{B}_a \end{bmatrix} = \begin{bmatrix} 0.0, 1.00, 0.00, 0.0 \\ 0.0, 0.67, 0.33, 0.0 \\ 0.0, 0.33, 0.67, 0.0 \\ 1.0, 0.00, 0.00, 0.0 \end{bmatrix} \tag{4.9}$$

Then transmit equation (4.9) into equation (4.8),

$$\begin{cases} \mu_A = \max[\min(0.2,0), \min(0.3,1), \min(0.2,0), \min(0.3,0)] \\ \mu_B = \max[\min(0.2,0), \min(0.3,0.67), \min(0.2,0.33), \min(0.3,0)] \\ \mu_C = \max[\min(0.2,0), \min(0.3,0.33), \min(0.2,0.67), \min(0.3,0)] \\ \mu_D = \max[\min(0.2,1), \min(0.3,0), \min(0.2,0), \min(0.3,0)] \end{cases} \tag{4.10}$$

So the solution are μ_A=0.3, μ_B=0.3, μ_C=0.3, μ_D=0.2. According to MM the security grade could be A, B, or C, it is advised to select C for safe. The engineers could take some measures according the result.

5. SEISMIC PERFORMANCE EVALUATION OF THE EXISTING CURTAIN WALL

Seismic performance of the existing curtain wall was not attracted enough attention for many years. The reason is that 1) there are few earthquakes occurred since the curtain wall come into being and 2) the weight of the curtain wall is smaller than the main structure and thus the earthquake action is not primary in seismic design and 3) seismic research work on the curtain wall is not enough. However, it is very necessary to appraise the seismic performance of curtain wall. Fuzzy theory was introduced in the following passage.

The method in this part is almost the same as the one in part 4 in this paper, but the purpose is different.

5.1. General Rules

Distinguish the seismic hazard members and the seismic unhazard members according the risk seismic evaluation method, then the s was worked out with equation (5.1) below according to the current codes and specifications.

$$s_i = n_d / n \times 100\% \tag{5.1}$$

Where s_i = seismic hazard members percentage of the curtain wall, i= parts of the curtain wall, n_d = number of seismic hazard members, n = number of total members being investigated.

Grade a, b, c, d was decided by the percentage of the HP. Suppose s=0% for grade a, s=5% for grade b, s=30% for grade c, s=100% for grade d. In the mid space between each grade, linear function was adopted. Seismic performance classifications of curtain wall system, as were shown in table 5.1.

Table 5.1 Seismic performance classifications of curtain wall system

Grade	Security Performance
A	Intact in a whole and no obvious damage and all the members are satisfied the seismic requirement.
B	Several members were slightly damaged, many of them satisfied the seismic requirement.
C	The appearance is serious in a whole, quite a few members are slightly damaged, many of them satisfied the seismic requirement closely.
D	Do not satisfied the seismic requirement in a whole

Membership function of grade a, b, c and d are supposed as bellow (hidden frame glass curtain wall),

$$\mu_a = \begin{cases} 1, (s = 0\%) \\ 0, (0\% < s \le 100\%) \end{cases} \tag{5.2}$$

$$\mu_b = \begin{cases} 1, (s \le 5\%) \\ \dfrac{30\% - s}{25\%}, (5\% < s \le 30\%) \\ 0, (30\% < s \le 100\%) \end{cases} \tag{5.3}$$

$$\mu_c = \begin{cases} 0, (s \le 5\%) \\ \dfrac{s - 5\%}{25\%}, (5\% < s \le 30\%) \\ \dfrac{100\% - s}{70\%}, (30\% < s \le 100\%) \end{cases} \tag{5.4}$$

$$\mu_d = \begin{cases} 0, (s \le 30\%) \\ \dfrac{s - 30\%}{70\%}, (30\% < s \le 100\%) \end{cases} \tag{5.5}$$

Transit the acquired percentage p into equation (5.2) ~ (5.5), the membership degree to the grade a, b, c, d of curtain wall parts such as panel, support system, adhesive and anchoring members could be got.

$\underset{\sim}{B}_s = \{\mu_{as}, \mu_{bs}, \mu_{cs}, \mu_{ds}\}$, $\underset{\sim}{B}_p = \{\mu_{ap}, \mu_{bp}, \mu_{cp}, \mu_{dp}\}$, $\underset{\sim}{B}_c = \{\mu_{ac}, \mu_{bc}, \mu_{cc}, \mu_{dc}\}$, $\underset{\sim}{B}_a = \{\mu_{aa}, \mu_{ba}, \mu_{ca}, \mu_{da}\}$.

Therefore, the evaluation matrix $\underset{\sim}{R}$ is $$\underset{\sim}{R} = \begin{bmatrix} \underset{\sim}{B}_p \\ \underset{\sim}{B}_s \\ \underset{\sim}{B}_c \\ \underset{\sim}{B}_a \end{bmatrix} = \begin{bmatrix} \mu_{as}, \mu_{bs}, \mu_{cs}, \mu_{ds} \\ \mu_{ap}, \mu_{bp}, \mu_{cp}, \mu_{dp} \\ \mu_{ac}, \mu_{bc}, \mu_{cc}, \mu_{dc} \\ \mu_{aa}, \mu_{ba}, \mu_{ca}, \mu_{da} \end{bmatrix} \tag{5.6}$$

Table 5.2 Seismic performance weight vector values
of curtain wall

Curtain wall type		Weight vector A^T
Glass curtain wall	Framed glass curtain wall	[0.2, 0.3, 0, 0.5]
	Hidden framed glass curtain wall	[0.15, 0.3, 0.15, 0.4]
	Partial Hidden framed glass curtain wall	[0.2, 0.35, 0.1, 0.35]
Steel plate or aluminum panel curtain wall		[0.1, 0.4, 0, 0.5]
Concrete panel, porcelain enamel panel or stone curtain wall		[0.2, 0.4, 0, 0.4]

Considering the importance of each part of the curtain wall, the weight factor vector $\underset{\sim}{A}$ should be set subjectively according to the experience. Different types of the curtain wall have different $\underset{\sim}{A}$, as shown in table 4. If $\underset{\sim}{A}=[0.15,0.3,0.15,0.4]^T$, after compound operation of the fuzzy matrix, the evaluation result is

$$\underset{\sim}{B} = \underset{\sim}{A} * \underset{\sim}{R} = \{\mu_A, \mu_B, \mu_C, \mu_D\} \tag{5.7}$$

Where, μ_A = membership degree to grade A, μ_B = membership degree to grade B, μ_C = membership degree to grade C, μ_D =membership degree to grade D, as illustrated in equation (5.8).

Calculator M（∩， ∪）was applied in equation (4.17)

$$\begin{cases} \mu_A = \max[\min(0.15, \mu_{ap}), \min(0.3, \mu_{as}), \min(0.15, \mu_{ac}), \min(0.4, \mu_{aa})] \\ \mu_B = \max[\min(0.15, \mu_{bp}), \min(0.3, \mu_{bs}), \min(0.15, \mu_{bc}), \min(0.4, \mu_{ba})] \\ \mu_C = \max[\min(0.15, \mu_{cp}), \min(0.3, \mu_{cs}), \min(0.15, \mu_{cc}), \min(0.4, \mu_{ca})] \\ \mu_D = \max[\min(0.15, \mu_{dp}), \min(0.3, \mu_{ds}), \min(0.15, \mu_{dc}), \min(0.4, \mu_{da})] \end{cases} \tag{5.8}$$

The membership grade was acquired on the maximum membership law (MM), thus, if $\mu_A = \max(\mu_A, \mu_B, \mu_C, \mu_D)$, the seismic performance of the curtain wall is grade A, if

$\mu_B = \max(\mu_A, \mu_B, \mu_C, \mu_D)$, the seismic performance of the curtain wall is grade B, if
$\mu_C = \max(\mu_A, \mu_B, \mu_C, \mu_D)$, the seismic performance of the curtain wall is grade C, if
$\mu_D = \max(\mu_A, \mu_B, \mu_C, \mu_D)$, the seismic performance of the curtain wall is grade D. If two or more membership degree above is equal from each other, the lower security grade should be selected.

5.2. Example 2

There is hidden framed glass curtain wall. The hazard member percentage is 10% for panel, 20% support system, 30% for adhesive and 0% for anchoring members after investigation. Please estimate the security performance of the curtain wall.
Solve, transit p=[10%,20%,30%,0%] into equation (5.2) ~(5.5),

$$\underset{\sim}{R} = \begin{bmatrix} \underset{\sim}{B}_p \\ \underset{\sim}{B}_s \\ \underset{\sim}{B}_c \\ \underset{\sim}{B}_a \end{bmatrix} = \begin{bmatrix} 0.0, 0.80, 0.20, 0.0 \\ 0.0, 0.40, 0.60, 0.0 \\ 0.0, 0.00, 1.00, 0.0 \\ 1.0, 0.00, 0.00, 0.0 \end{bmatrix} \tag{5.9}$$

Then transmit equation (5.9) into equation (5.8),

$$\begin{cases} \mu_A = \max[\min(0.15,0), \min(0.3,0.8), \min(0.15,0.2), \min(0.4,0)] \\ \mu_B = \max[\min(0.15,0), \min(0.3,0.4), \min(0.15,0.6), \min(0.4,0)] \\ \mu_C = \max[\min(0.15,0), \min(0.3,0), \min(0.15,1.00), \min(0.4,0)] \\ \mu_D = \max[\min(0.15,1), \min(0.3,0), \min(0.15,0), \min(0.4,0)] \end{cases} \tag{5.10}$$

So the solution are μ_A=0.3, μ_B=0.3, μ_C=0.15, μ_D=0.15. According to MM the security grade could be A or B, it is advised to select B for safe. Some measures should be taken according the result.

6. CONCLUSION

Analysis and discussion on the security performance of the existing curtain wall was executed utilizing fuzzy theory. Relative theory and methodology was put forward to evaluate the security and seismic performance of the curtain wall. The result of this paper might be helpful to the existing curtain wall security estimation and the practice on site.

7. ACKNOWLEDGEMENT

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