Study on evaluation indices and methods of seismic reparability for RC buildings

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SUMMARY:
Evaluating the reparability of RC buildings under earthquake action reasonably is an important part of seismic behavior assessment and performance-based design. In this paper, the reparability is evaluated by the following four indices: repair to replacement cost ratio, repair to replacement time ratio, repair workload ratio and repair difficulty index. Meanwhile, this paper chooses component damage factor as object, and establishes the mathematical model by using the fuzzy control theory. The reparability is classified into four classes according to the fuzzy comprehensive evaluation for RC buildings under earthquake action. And the calculation methods of the four indices are also presented in the paper. Analysis results show that the evaluation indices and methods proposed in this paper are objective and reliable which can provide reference for seismic behavior assessment and performance-based design.

Keywords: RC buildings, Seismic reparability, Performance-based design, Fuzzy comprehensive evaluation

1. GENERAL INSTRUCTIONS

The basic methods for structure seismic design of most countries in the world follow the capacity-ductility rule (Dooley and Bracci 2001). It has been widely known that buildings will be subjected to different levels of damage under large earthquakes. Therefore, reasonable evaluation of seismic reparability for RC buildings is an important part of seismic behavior assessment and realizing performance-based design (Yingmin Li et al. 2012). This paper focuses on studying the evaluation indices and establishing the evaluation model which can provide reference for related researches.

The main factors of seismic reparability for RC buildings are repair cost, repair time, repair workload, and repair difficulty. To make the evaluation model more general, the relative indices which are repair to replacement cost ratio, repair to replacement time ratio, repair workload ratio and repair difficulty index are used in this paper. According to characteristics of the evaluation indices, the reparability mathematical model for RC buildings is established by using the fuzzy comprehensive evaluation method.

2. COMPONENT DAMAGE FACTOR AND EVALUATION INDEX

2.1. Component damage factor

The damage of RC buildings or components subjected to earthquake action needs quantitative evaluation in many cases. The damage of structures or component is not only related to maximum deformation, but also to cumulative hysteretic energy. Thus the reasonable damage indices should take into account of these two factors. The Park–Ang damage index (Park and Ang 1985) and its modifications revised by large amounts of data are widely recognized in the world. So the component damage factor (DF) is evaluated by using the modified Park-Ang damage index (Kunnath et al. 1992) in this paper, as shown in Eqn. 2.1.

$$DF = \frac{\theta_m - \theta_r}{\theta_u - \theta_r} + \frac{\beta}{M_y \theta_u} \int dE_h \tag{2.1}$$

Where θ_m = member end rotation, θ_r = recoverable rotation during unloading, θ_u = ultimate rotation (capacity) under monotonic static loading, β = a non-negative non-dimensional parameter, M_y = yield moment capacity and $\int dE_h$ = cumulative hysteretic energy. This definition assigns '0' to the undamaged state and greater than '1' to the fully collapsed state.

This paper chooses the component damage factor as the object to evaluate the seismic reparability.

2.2 Evaluation indices

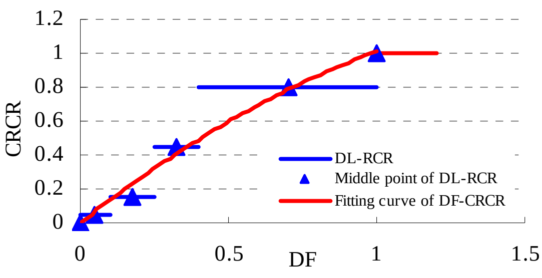
Building repair to replacement cost ratio (BRCR). The BRCR is defined as the ratio of repair cost to replacement cost. It represents the relative repair cost of the building after a strong earthquake happened. MOHU(2005) constructs the relationship of damage level to repair to replacement cost ratio for RC buildings. And Park and Ang (1987) show the relationship between damage factor and damage level. Therefore, the relationship of the component damage level to component repair to replacement cost ratio (CRCR) can be built based on MOHU(2005) and Park and Ang (1987). Then fitting the middle point of each damage level using polynomial fitting method, we can get the formula between component damage factor and CRCR, as illustrated in Fig. 2.1. (The blue line is the relationship of the damage level and repair cost, the blue point is the middle point of each damage level and the red curve is the fitting curve of DL-CRCR). The polynomial fitting curve conforms very closely to the data because the fitting degree (R^2) is as high as 0.99. The Eqn. 2.2 is used to express the DF-CRCR relationship in this paper.

$$CRCR = \begin{cases} -0.37DF^2 + 1.37DF, & DF \le 1 \\ 1, & DF > 1 \end{cases} \tag{2.2}$$

As the component repair cost is closely related to the component volume, the ratio of the component volume to the volume of all structure components is used as the weight when establishing BRCR. The calculation method of BRCR is shown in Eqn. 2.3.

$$BRCR = \sum_{i=1}^{N_W} CRCR_{W,i} \times \frac{V_{W,i}}{V} + \sum_{i=1}^{N_C} CRCR_{C,i} \times \frac{V_{C,i}}{V} + \sum_{i=1}^{N_B} CRCR_{B,i} \times \frac{V_{B,i}}{V} \tag{2.3}$$

Where $CRCR_{W,i}, CRCR_{C,i}, CRCR_{B,i}$ represent the component repair to replacement cost ratio of wall, column and beam of component *i*, respectively. While $V_{W,i}, V_{C,i}, V_{B,i}, V$ represent volume of wall, column, beam of the component *i* and the total volume of structure components, respectively. And N_W, N_C, N_B are the total number of walls, columns and beams of the building, respectively.



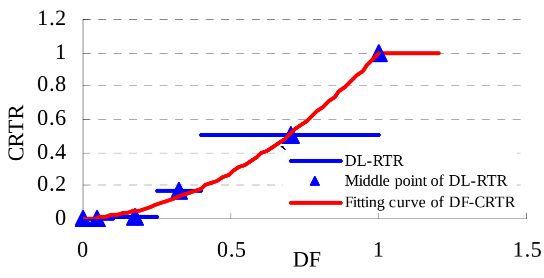


Figure 2.1. *DF-CRCR* Relationship **Figure 2.2.** *DF-CRTR* Relationship

Building repair to replacement time ratio (BRTR). The BRTR is defined as the ratio of repair cost to replacement time which means the relative repair time of the building after a strong earthquake happened. And this index can indicate the relative interruption time of the normal use of the building function. The relationship component damage level and component repair to replacement time ratio (CRTR) can be derived out through the reference (Park and Ang 1987) and the reference (稲田達夫 2008), in the same way used above. Then we can get DF-CRTR curve which is shown in Fig. 2.2. (The blue line is the relationship of the damage level and repair time, the blue point is the middle point of each damage level and the red curve is the fitting curve of DL-CRTR) by fitting the middle point of each damage level using the polynomial fitting method. The polynomial fitting curve conforms very closely to the data, as the fitting degree (R^2) is as high as 0.99. With the component damage factor, CRTR can be estimated by Eqn. 2.4.

$$CRTR = \begin{cases} 0.89DF^2 + 0.11DF, & DF \le 1 \\ 1, & DF > 1 \end{cases} \quad (2.4)$$

The ratio of the component volume to the volume of all structure components is used as the weight in establishing BRTR because the component repair time is also closely related to the component volume. The BRCR is expressed in Eqn. 2.5.

$$BRTR = \sum_{i=1}^{N_W} CRTR_{W,i} \times \frac{V_{W,i}}{V} + \sum_{i=1}^{N_C} CRTR_{C,i} \times \frac{V_{C,i}}{V} + \sum_{i=1}^{N_B} CRTR_{B,i} \times \frac{V_{B,i}}{V} \quad (2.5)$$

Where $CRTR_{W,i}$, $CRTR_{C,i}$, $CRTR_{B,i}$ represent the component repair to replacement time ratio of walls, columns and beams of component *i*, respectively.

Building repair workload ratio (BRWR). The BRWR is defined as the ratio of the number of component which needs to be repaired to the total component number of buildings. The reparability is better if the BRWR is smaller when the other evaluation indices are at the same level. The BRWR is shown in Eqn. 2.6

$$BRWR = \frac{N_{W(DF_{W,i}>0)} + N_{C(DF_{C,i}>0)} + N_{B(DF_{B,i}>0)}}{N_W + N_C + N_B} \quad (2.6)$$

Where $N_{W(DF_{W,i}>0)}$, $N_{C(DF_{C,i}>0)}$, $N_{B(DF_{B,i}>0)}$ mean the total number of walls, columns and beams which need to be repaired, respectively.

Building repair difficulty index (BRDI). It means the repair difficulty of buildings after a strong earthquake happened. The building damage factor or the component damage factor can be used for evaluation the repair difficulty directly. The larger the damage factor is, and the buildings would be more difficult to be repaired. Meanwhile, the position and damage factor of the floor are set as the weight when the BRDI is established. The story repair difficulty index (SRDI) and BRDI are shown in Eqn. 2.7, Eqn. 2.8, respectively.

$$SRDI_i = \frac{\sum_{j=1}^{N_{W,i}} DF_{W,j}{}^2 + \sum_{j=1}^{N_{C,i}} DF_{C,j}{}^2 + \sum_{j=1}^{N_{B,i}} DF_{B,j}{}^2}{\left(\sum_{j=1}^{N_{W,i}} DF_{W,j} + \sum_{j=1}^{N_{C,i}} DF_{C,j} + \sum_{j=1}^{N_{B,i}} DF_{B,j} \right)} \tag{2.7}$$

$$BRDI = \frac{\sum_{i=1}^{n} (n+1-i) SRDI_i{}^2}{\sum_{i=1}^{n} (n+1-i) SRDI_i} \tag{2.8}$$

Where n is the total story of the building. And $DF_{W,j}, DF_{C,j}, DF_{B,j}$ are the damage factors of the walls, columns and beams of the floor *i*, respectively.

3. FUZZY EVALUATION METHODS

3.1 Fuzzy comprehensive model for reparability

The fuzzy comprehensive evaluation method makes a comprehensive evaluation of the factors being evaluated by the application of the fuzzy linear transformation theory and principle of maximum degree. The seismic reparability is classified into four classes according to the characteristics of the reinforced concrete buildings. The evaluation set is defined in Eqn. 3.1.

$$V = \{v_1, v_2, v_3, v_4\} \tag{3.1}$$

Where v_1 = Easy to repair, v_2 = Moderate to repair, v_3 =Difficult to repair, v_4 = Beyond repair. The details of the evaluation set can be checked in Section 3.2.2.

The evaluation factors set are established in Eqn. 3.2 according to the above analysis.

$$U = \{u_1, u_2, u_3, u_4\} \tag{3.2}$$

Where u_1, u_2, u_3, u_4 represents BRCR, BRTR, BRWR and BRDI, respectively.

As a result, we can get a mathematical model for the fuzzy comprehensive evaluation of reparability (Puyin and Mengda 1998), which can be represented by Eqn. 3.3.

$$\underset{\sim}{B} = A \circ R = (b_1, b_2, b_3, b_4) \tag{3.3}$$

Where $\underset{\sim}{B}$ is subset on the evaluation set V. A is the weight vector corresponding to the evaluation factors set. R is fuzzy comprehensive evaluation matrix. $\circ$ is the evaluation function. The weighted average operator $M(\bullet, +)$ which can take all the evaluation factors into consideration is used in this paper (Puyin and Mengda 1998).

3.2 Membership functions

3.2.1 Determining membership functions

The membership degree method is the basic idea of fuzzy mathematics. The membership function means how the evaluation factor u_j belong to the evaluation set v_i. It is difficult to distinguish the two neighbouring adjacent reparability levels, such as Easy to repair and Moderate to repair. But it may easily differentiate Easy to repair from Difficult to repair. Consequently, the membership functions should cross over two reparability levels. Based on the variation trend of indices and evaluation factors, the paper uses the mountain-shaped subordinated functions of fuzzy mathematics in the computation of the membership functions (Puyin and Mengda 1998), as shown in Eqn. 3.4 to Eqn. 3.6.

$$\mu_{v1}\left(u_j\right)=\begin{cases}1, & u_j \le d_1 \\ \dfrac{1}{2}+\dfrac{1}{2}\sin\pi\left(\dfrac{1}{2}+\dfrac{u_j-d_1}{d_2-d_1}\right), & d_1 < u_j \le d_2 \\ 0, & u_j > d_2\end{cases} \tag{3.4}$$

$$\mu_{vi}\left(u_j\right)=\begin{cases}0, & u_j \le d_{i-1} \\ \dfrac{1}{2}+\dfrac{1}{2}\sin\pi\left(\dfrac{u_j-d_{i-1}}{d_i-d_{i-1}}-\dfrac{1}{2}\right), & d_{i-1}< u_j \le d_i \\ \dfrac{1}{2}+\dfrac{1}{2}\sin\pi\left(\dfrac{u_j-d_i}{d_{i+1}-d_i}+\dfrac{1}{2}\right), & d_i < u_j \le d_{i+1} \\ 0, & u_j > d_{i+1}\end{cases} \quad \left(i=2,3\right) \tag{3.5}$$

$$\mu_{v4}\left(u_j\right)=\begin{cases}0, & u_j \le d_3 \\ \dfrac{1}{2}+\dfrac{1}{2}\sin\pi\left(\dfrac{u_j-d_3}{d_4-d_3}-\dfrac{1}{2}\right), & d_3< u_j \le d_4 \\ 1, & u_j > d_4\end{cases} \tag{3.6}$$

Where $d_i\left(i=1,2,3,4\right)$ is the maximum critical value of evaluation factor j about the reparability degree *i*.

3.2.2 Maximum critical value of each reparability level

Based on the qualitative description of damage level in the reference (MOHU2000), the reparability level can be defined as follows.

Easy to repair: %5 of the walls, columns and beams undergoing slightly damage. The demand repair cost, repair time and repair workload are very low. Moreover, it is easy to repair.

Moderate to repair: Less than 30% of the walls, columns and beams damage slightly or 5% of the structure components damage moderately. The demand repair cost, repair time and repair workload are not excessively high. And it may have a little difficult to repair the buildings.

Difficult to repair: Less than 30% of the walls, columns and beams are badly damaged. A small part of structure components need to be replaced, and the demand repair cost, repair time and repair workload are high. And it is difficult to be repaired.

Beyond repair: More than 50% of the walls, columns and beams badly damaged. A lot of structures components need to be replaced. The demand repair cost, repair time and repair workload are very high. And it is beyond repair.

The maximum critical value of each evaluation factors corresponding to each reparability level are displayed in Table 3.1, according to the qualitative description of the reparability.

Table 3.1. Maximum Critical Value of Each Reparability Level

Evaluation factor	Easy to repair	Moderate to repair	Difficult to repair	Beyond repair
BRCR	7.5e-3	3.4e-2	0.24	0.5
BRTR	5.6e-4	5.8e-3	0.15	0.5
BRWR	0.05	0.175	0.3	0.5
BRDI	0.1	0.25	0.4	1

3.3 The value of the weight

The four evaluation factors are not as significant as each other. The importance of the factors is represented by the weight in the paper. Considering the four evaluation factors are rich in technicality, the expert arranging law may be more objective when we establish the weight. The evaluation factors are marked as 1, 2, 3, and 4 according to the importance by experienced experts. The marked number is the rank of the factor. Plus all the rank of the factor, we can get the rank sum. R_i is the rank sum of factor *i*. The weight formula for factor *i* is expressed in Eqn .3.7 (Puyin and Mengda 1998).

$$A_i = \frac{\left(m\left(1+4\right)-R_i\right)}{4\left(1+4\right)m/2} = \frac{5m-R_i}{10m} \tag{3.7}$$

It is Easy to verify that the sum of the weight of all the four factors is equal to 1, which meets the normalization condition.

3.4 Reparability index

The reparability level could be determined according to principle of maximum degree, after obtaining the subset $\underset{\sim}{B}$ according to Eqn. 3.3. But if we do that, it could not take full advantage of the information $\underset{\sim}{B}$ contained, and the evaluation result would be a bit of rough. The paper uses the reparability index $RI(RI \in [0,1])$ to represent the reparability. The larger the RI is, the easier the repair would be. Therefore, in order to get the RI, the subset $\underset{\sim}{B}$ is treated as follows.

Firstly, decide level parameters c_i of each evaluation level v_i of evaluation set V. The $c_i - v_i$ relationship is listed in Table 3.2.

Table 3.2. Level Parameter of Each Evaluation Level

Reparability Level v_i	Easy to repair	Moderate to repair	Difficult to repair	Beyond repair
Level Parameter c_i	1	0.67	0.33	0
BRTR	5.6e-4	5.8e-3	0.15	0.5
BRWR	0.05	0.175	0.3	0.5
BRDI	0.1	0.25	0.4	1

Then generate the level parameters $C = \{1,0.67,0.33,0\}^T$, calculate out the RI by formula $RI = \underset{\sim}{B} \bullet C$, after normalization processing of subset $\underset{\sim}{B}$.

3.5 The fuzzy comprehensive evaluation process of reparability

Based on the above analysis, the operating procedures of the fuzzy comprehensive evaluation of the reparability for reinforced concrete buildings are listed as follows.

Define the evaluation set $V = \{v_1, v_2, v_3, v_4\}$, that is determine the reparability level of different reparability.

Define the evaluation set $U = \{u_1, u_2, u_3, u_4\}$, select the evaluation factor and define the weight vector A by the expert arranging law.

Calculate the values of each evaluation factor, BRCR, BRTR, BRWR and BRDI according to the components damage factors.

Carry out the values of membership function $\mu_{vi}(u_j)$, and form the fuzzy comprehensive evaluation matrix R.

Get the subset $\underset{\sim}{B}$ using $\underset{\sim}{B} = A \circ R$.

Determine the reparability level referring to the principle of maximum degree, and calculate the RI.

4. EXAMPLE OF APPLICATION

A six-floor reinforced concrete frame building is designed according to the *Code for seismic design of buildings* (MOHU 2011). Fig. 4.1. is the plan of the building. The cross section of column is $550mm \times 550mm$ and the cross section of beam is $250mm \times 550mm$. One of the frames shown in Fig. 4.2. is taken out for analysis because the structure is regular in plan and elevation.

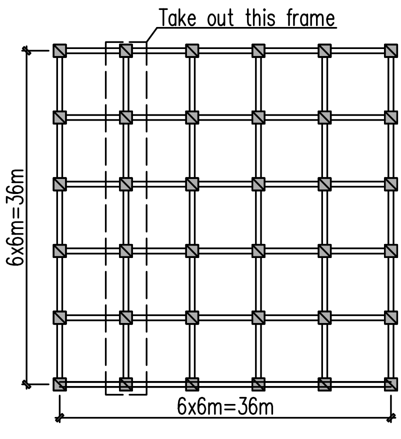


Figure 4.1. Plan of the building

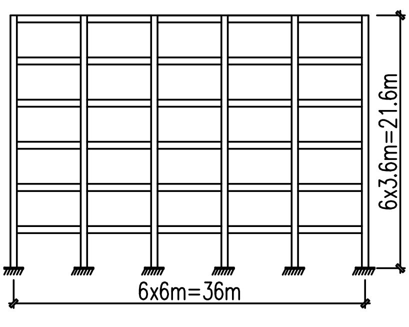


Figure 4.2. Elevation of the building

Three seismic waves are selected as the input of the analysis based on the natural period of the structure and the site characterization. Assuming that the weight vector of the evaluation factor is $A = \{0.4, 0.2, 0.1, 0.3\}$. Then calculate the reparability of the building when the PGA increasing from $2.2\,m/s^2$ to $5.1\,m/s^2$. The reparability index curve is shown in Fig. 4.3.

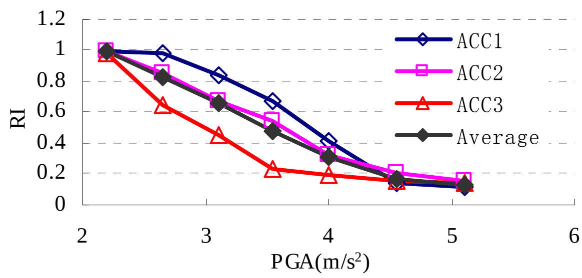


Figure 4.3. Reparability index curve of the building

Table 4.1. The Reparability Level of The Building

PGA(m/s^2)	2.2	3.1	4	5.1
Reparability level	Easy to repair	Moderate to repair	Beyond repair	Beyond repair

The result show that the reparability index of the building reduces from 0.99 to 0.13 as the PGA increasing from $2.2\,m/s^2$ to $5.1\,m/s^2$. The reparability level is shown in Table 4.1. Therefore the evaluation model proposed in the paper is objective and reliable. The results can be used in evaluating the seismic behavior of building.

5. CONCLUSIONS

In this paper, the reparability is evaluated by four indices: repair to replacement cost ratio, repair to replacement time ratio, and repair workload ratio and repair difficulty index according to the main factors which play important role in reparability. Meanwhile, this paper chooses component damage factor as the object, and establishes fuzzy comprehensive evaluation model for reparability by using the fuzzy control theory. And the relationship between the component damage factor and the calculation methods of the four evaluation factors are presented in the paper. Result of the application example shows that the evaluation indices and methods proposed are objective and reliable which can provide reference for seismic behavior assessment and performance-based design.

However, the relationship between component damage factor and *BRCR* and *BRTR* are approximately obtained according to the relationship between building damage factor and those two evaluation factors. Besides, the reparability of building may be affected by the damage of non-structural components and the contents of the buildings. These factors need to be supplemented and improved in further research.

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