MULTI-HIERARCHICAL DURABILITY ASSESSMENT OF EXISTING REINFORCED-CONCRETE STRUCTURES

Durability assessment of reinforced-concrete structures

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Abstract

Durability of an existing reinforced concrete structure is one of the most important problems for its users and owners. However, no systematic durability assessment approach exists currently. The assessment results vary in relation to the knowledge, expertise, and partiality of the assessor. Additionally, most assessment may not focus on all the key system parameters that affect structural durability. This paper aims at establishing a systematic durability assessment approach for R.C. Structures. The development of such an approach would help to identify all major parameters that affect structural durability and in addition, would enable assessors to collect both qualitative as well as quantitative information in a standard format for any given reinforced concrete structure. Furthermore, such a systematic assessment approach would provide a fair and objective way for analyzing and dealing with data collected by field inspection. Firstly, by Saaty's ratio scaling method, which scientifically quantifies the subjective information of expert judgments. Secondly, on basis of the properties of entropy, which combines the subjective information of expert judgments with the intrinsic information of assessment parameters. Then, taking gray relation grade as criterion, which obtains the deterioration degree and deterioration rate for a given structure. Finally, based on the assumption that deterioration varies with time exponentially, it gives the present performance and residual service life for any existing reinforced concrete structure.

Keywords: Reinforced concrete structure, Analytic Hierarchy Process, information entropy, gray relation grade, residual service life prediction

1 Introduction

Durability is one of the main features of an existing reinforced concrete structure, and it is supposed to be assessed regularly in case failure occurs. But unfortunately, no systematic durability assessment approach has been established up to now. In finding such a systematic approach, there are three problems to be solved: how to unify durability assessment with residual service life prediction, how to use the knowledge on durability to identify the key system parameters and what mathematical methods to use to guarantee the objectivity of assessment result. This paper presents a solution to each of the above problem. Firstly, it suggests that two systems, namely deterioration degree system (DDS) and deterioration rate system (DRS), be established for an existing structure. I provide the key parameters, applicable in general cases, for each system. Finally, using Analytic Hierarchy Process (AHP), Information Entropy Formula and Gray Relation Grade Theory, it minimizes the partiality of the assessor to a large extent. Durability of an existing R.C. structure is characterized as two complex systems with each comprising many interrelated parameters. All these parameters are arranged into different levels and grouped into subjective/qualitative and objective/quantitative parameters. The former cannot be known precisely, or in words of Gray Theory, they are gray. Therefore, it is in reason to use AHP and Gray Theory in durability assessment.

2 Steps of multi-hierarchical durability assessment

2.1 Identification of the key parameters

For an existing reinforced concrete structure, there are generally two sets of system parameters: One is for DDS and the other for DRS. Each set consists of a recursive hierarchy composed of three levels: structure, component and factor.

The DDS parameters and DRS parameters are listed in Table 1 (Wang 1996).

Table 1: Key parameters for DDS and DRS

Structure Level	Component Level	Factor Level	
DDS	Beam, Column, Wall, Foundation, and others.	Qualitative/Subjective	Concrete longitudinal cracking, scaling and peeling; AAR and corrosion marks and so on.
		Quantitative/Objective	Percentage of steel corrosion, percentage of strength reduction of concrete, concrete carbonation depth and so on.
DRS	Beam, Column, Wall, Foundation, and others.	Qualitative/Subjective	Climate of service area, including temperature, humidity, concentration of harmful gases, frequency of freeze-thaw alternation, concentration of corrosive materials, corrosion protective measures, and so on.
		Quantitative/Objective	Intensity of polarized electricity, potential of steel corrosion, polarized impedance and so on.

2.2 Determination of gray relation coefficients

2.2.1 Value Assignment of Data Set

It can be seen from Table 1 that both systems have qualitative as well as quantitative parameters. According to the maximum resolving power of the human brain, qualitative parameters are graded into five ranks, which are valued 5, 4, 3, 2, and 1. Usually, a qualitative parameter is evaluated through expert judgements, while a quantitative parameter is determined by measurements. Thus, one can obtain the values of all parameters subordinate to one common higher-level parameter. All these values constitute the practical set, expressed as

$$\mathbf{C} = (C_1 \quad C_2 \cdots C_n)^{\mathrm{T}},$$

where: C_j = is the practical value of the jth parameter.

Each parameter C_j has a predetermined optimal value, which is denoted by C_j^*. All the optimal values constitute the optimal set, expressed as $\mathrm{C}^* = (C_1^* \quad C_2^* \ \ldots \ C_n^*)^{\mathrm{T}}$, where C_j^* is the optimal value of the jth parameter.

Through comparison of the practical set to the optimal set, the situation of a given structure can be determined.

2.2.2 Data Normalization

In many cases, the units and magnitudes of different parameters are incompatible, so it is necessary to normalize the data.

Suppose C_j varies in the range $\left[C_j^L, C_j^U\right]$, then its normalized value F_j is

$$F_j = \frac{C_j^U - C_j}{C_j^U - C_j^L} \text{ (for positive parameters)} \qquad \textbf{(1)}$$

$$F_j = \frac{C_j - C_j^L}{C_j^U - C_j^L} \text{ (for negative parameters)} \qquad \textbf{(2)}$$

Where negative parameter is defined as one with which deterioration increases. Obviously, $F_j \in [0,1]$ and has no dimension.

The normalized value of any parameter is 0. This can be derived from equation (1) and (2). There are two cases. (1) For positive parameter, $C_j^* = C_j^U$ and (2) for negative parameter, $C_j^* = C_j^L$. Both cases lead to $F_j^* = 0$, which indicates that the optimal set has a correspondence with the situation of no deterioration.

A number of engineering examples suggest varying value ranges for the parameters and optimal values are given in Table 2 with asterisks, while the others are the worst. For DDS, the worst values correspond to the condition that structural load carrying capacity decreases by 10%. For DRS, the worst values correspond to the condition that structural deterioration rate reaches the tolerance (preset as 1% per year in this paper). Either situation implies the failure of a structure.

Table 2: Varying ranges and optimal values of some parameters

Varying Range	Qualitative Parameter	Quantitative DD Parameters			Quantitative DD Parameters	
		Crack Width (mm)	Percentage of Steel Corrosion (%)	Percentage of Concrete Strength Reduction (%)	Steel Corrosion Rate (%/year)	Deterioration Rate (%/year)
Upper Bound	5*	0.6	5	10	0.5	1
Lower Bound	0	0*	0*	0*	0*	0*

2.2.3 Calculation of Gray Relation Coefficients

Using the normalized optimal set as a reference of the normalized practical set, the gray relation coefficient between F_j and F_j^*, denoted by b_j (Lu 1998), can be calculated by:

$$b_j = \frac{0.5}{1.5 - F_j} \quad \textbf{(3)}$$

2.3 Determination of parameter weight

2.3.1 Initial weight

(1) Formation of Judgement Matrix

By comparing the importance of all parameters subordinate to one common higher parameter, one can obtain the judgement matrix. Generally, if $C_j\,(j = 1,2,\cdots,n)$ are all subordinate to B, the judgement matrix is an n-D matrix, as listed in Table 3.

In Table 3, a_{ij} indicates the relative importance of parameter i vs. parameter j. To quantify a_{ij}, one can use Saaty's Ratio Scaling Method (See Table 4) (Chen and Lu 1998). (2) Calculation of Maximum Eigenvalue and Eigenvector of Judgement Matrix Computational methods for the maximum eigenvalue and its corresponding eigenvector have been introduced in many algebraic books, so unnecessary details are not given here.

Table 3: General form of judgement matrix

B_i	C_1	C_2	…	C_n
C_1	a_{11}	a_{12}	…	a_{1n}
C_2	a_{21}	a_{22}	…	a_{2n}
…	…	…	…	…
C_n	a_{n1}	a_{n2}	…	a_{nn}

Table 4: Judgement scales and meanings

Scales	Meanings
1	One parameter is as important as the other
2	One parameter is slightly more important than the other
3	One parameter is evidently more important than the other
4	One parameter is intensely more important than the other
5	One parameter is extremely more important than the other
reciprocal	$a_{ji}=1/a_{ij}$

(3) Checkup of Judgement Matrix Consistency

The consistency index for an *n*-D matrix is determined by

$$\mathrm{CI}=\frac{\lambda_{\max}-n}{n-1} \tag{4}$$

where $\lambda_{\max}$ =maximum eigenvalue, n =number of matrix dimension.

It must be pointed out that CI is function of *n*. That is to say, matrices with the same $\lambda_{\max}$ but different *n* values have different allowable consistency. Therefore, a new parameter RI, called average random consistency index, is introduced. RI can be assigned according to Table 5.

Table 5: Average random consistency index RI

n	3	4	5	6	7	8	9
RI	0.58	0.90	1.12	1.24	1.32	1.41	1.45

1-D or 2-D matrix always has complete consistency, so it is unnecessary to take consistency checkup. When *n* is larger than 2, the consistency can be checked up by the ratio

$$\mathrm{CR}=\frac{\mathrm{CI}}{\mathrm{RI}} \tag{5}$$

If $\mathrm{CR}<0.10$, the judgement matrix is deemed to have satisfying consistency, otherwise it should be modified until it arrives at satisfactory consistency.

On condition that the judgement matrix has satisfactory consistency, its eigenvector corresponding to the maximum eigenvalue is the initial weight *W*.

2.3.2 Parameter entropy

Initial weight reflects only the subjective expert experience. In most cases, parameters' magnitude also has an influence on the weight. Therefore, it is required that initial weight be modified by parameters' intrinsic information. This modification can be realized by introducing information entropy, which is formulated as (Lu 1998)

$$E_j = -\left(F_j \Big/ \sum_{j=1}^{n} F_j \right) \ln \left(F_j \Big/ \sum_{j=1}^{n} F_j \right), \quad j = 1,2,\cdots,n \qquad \textbf{(6)}$$

where E_j =entropy reflecting the importance of F_j.

2.3.3 Final weight

The final weight is given by

$$w_j = \frac{E_j W_j}{\sum_{j=1}^{n} E_j W_j}, \quad j = 1,2,\cdots,n \qquad \textbf{(7)}$$

It should be shown that w_j satisfies $0 \le w_j \le 1$; and $\sum_{j=1}^{n} w_j = 1$.

2.4 Calculation of assessment results on component level

Any assessment result on component level is actually weighted gray relation grade, which is given by:

$$S = \sum_{j=1}^{n} w_j b_j \qquad \textbf{(8)}$$

The geometrical meaning of S is the distance between the practical set and the optimal set. The larger the value S, the closer is the distance between practical set and optimal set.

2.5 Calculation of assessment result on structure level

In this step, assessment results on the component level are taken as parameter values on structure level. Structure assessment is carried out in the same procedure as the component assessment. The assessment result includes two assessment values: One is the DDA value, R, and the other, DRA value, $\dot{R}$.

2.6 Calculation of DD and DR on structure level

R and $\dot{R}$ are weighted gray relation grades between the practical set and optimal set for DDS and DRS, respectively. They can be used to countercalculate the equivalent normalized values. From equation (3), two equivalent normalized values F and $\dot{F}$ are derived as follows

$$F = 1. \quad \frac{0.}{R}, \quad \dot{} = 1\ 5 - \frac{0\ 5}{\dot{R}} \qquad \textbf{(9)}$$

$$\ddot{O} = F \times 10\%, \quad \dot{\Phi} = \dot{F} \times 1\% / \text{year} \qquad \textbf{(10)}$$

in which Φ =DD on structure level, $\dot{\Phi}$ =DR on structure level.

2.7 Prediction of structural service life

Suppose a structure has serviced for T years, during which it has undergone N repairs. If the i th repair occurred in the T_i th year, and the ratio of the added load carrying capacity to the initial load carrying capacity is h_i, then based on the assumption that deterioration varies with time exponentially, equations (11)(12) are tenable (Lu 1998):

$$aT^{b} + \sum_{i=1}^{N} h_i a (T - T_i)^{b} - \sum_{i=1}^{N} h_i = \Phi \tag{11}$$

$$abT^{b-1} + \sum_{i=1}^{N} h_i ab (T - T_i)^{b-1} = \dot{\Phi} \tag{12}$$

where a , b are called deterioration coefficient and deterioration exponent, respectively.

The residual service life of a structure, denoted by T_r, can be obtained from the equation

$$a(T + T_r)^{b} + \sum_{i=1}^{N} h_i a (T + T_r - T_i)^{b} - \sum_{i=1}^{N} h_i = 10\% \tag{13}$$

It can be known from equation (13) that residual service life is function of the service time, maintenance record, and assessment results.

3 Illustrative example

A one-bay and two-story portal frame to be assessed is shown in Figure 1. The frame is located in a coastal area and has been used for 10 years. Before being assessed, the frame underwent no repair. The data collected by field inspection are shown in Table 6.

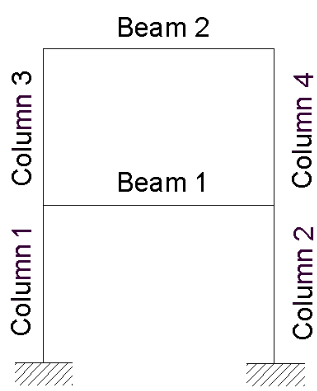

Fig. 1: One-bay and two-story frame

Table 6: Data collected by field inspection

Component			Beam 1	Beam 2	Column 1	Column 2	Column 3	Column 4
DDS	Qualitative	Overall Appearance	4.4	4.1	3.8	3.6	3.9	4.1
	Quantitative	Crack Width (mm)	0.09	0.12	0.21	0.24	0.27	0.21
		Percentage of Steel Corrosion %)	1.1	1.2	1.6	1.8	1.2	1.0
		Percentage of Concrete Deterioration (%)	1.5	2	2.5	2.5	2.0	2.0
DRS	Qualitative	Environmental Condition	3.6	3.4	3.0	3.0	3.6	3.7
	Quantitative	Steel Corrosion Rate (%/year)	0.05	0.07	0.12	0.14	0.09	0.06
		Deterioration Rate of Concrete Strength (%/year)	0.30	0.40	0.50	0.50	0.40	0.36

3.1 Determination of initial weight

The results are shown in Figures 2 and 3.

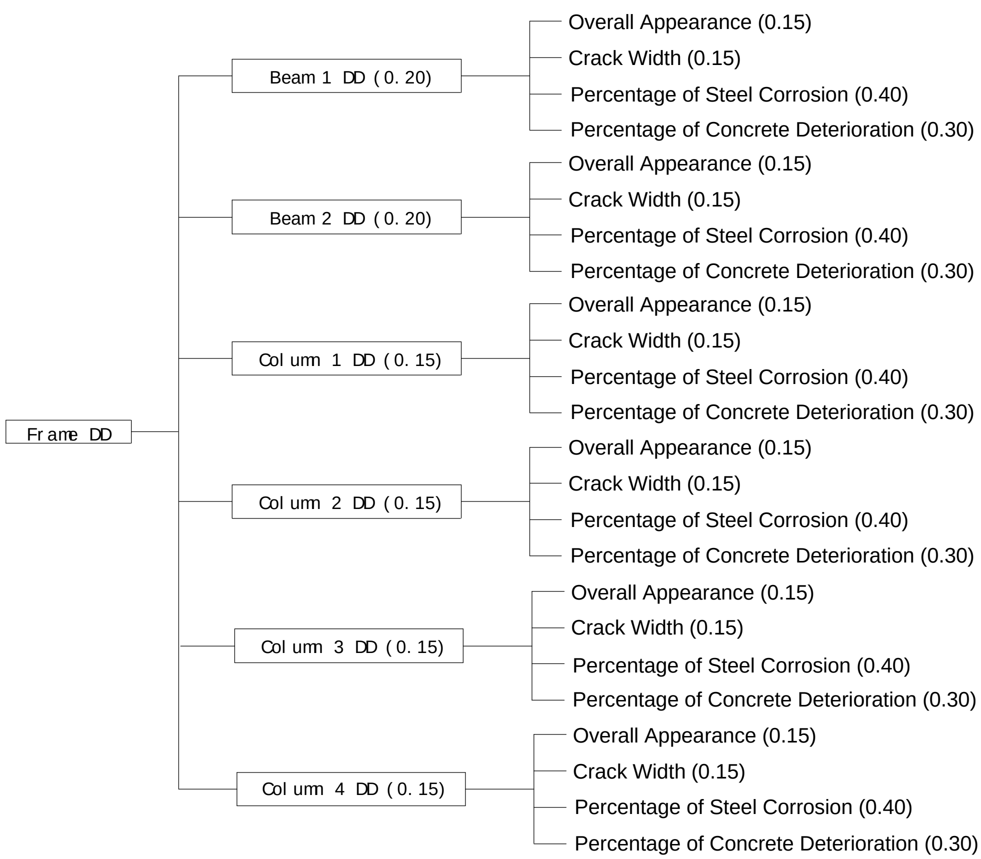

Fig. 2: Deterioration degree system and initial weight

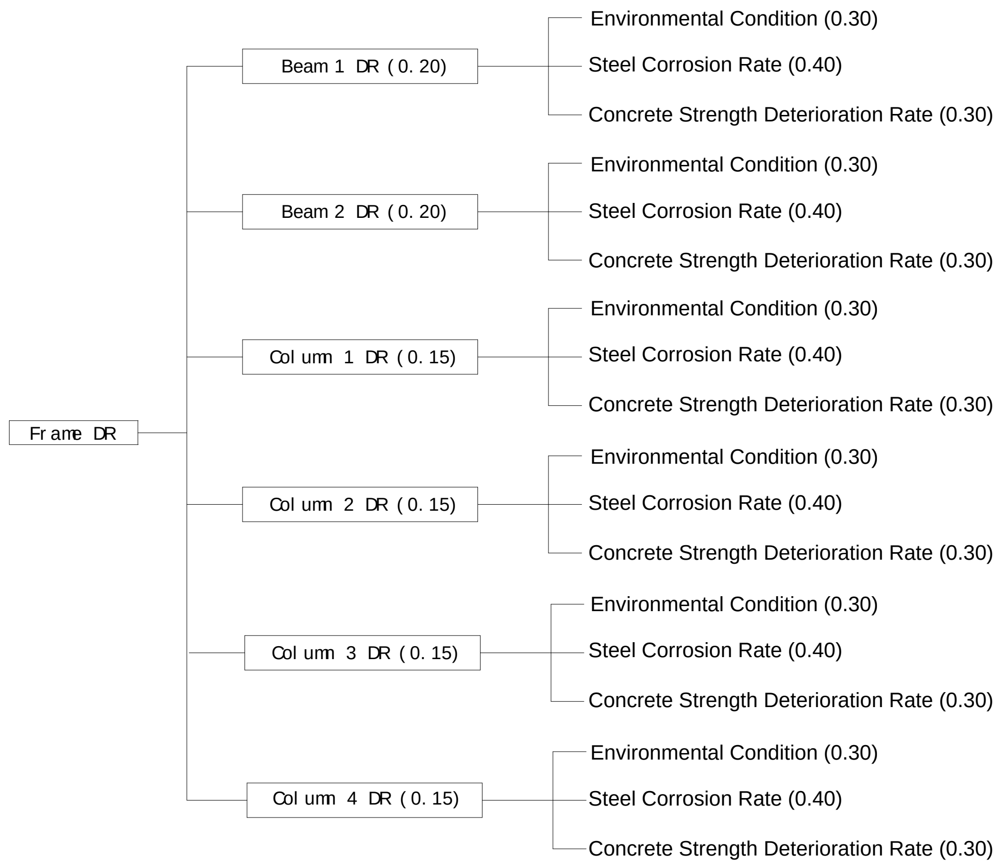

Fig. 3 Deterioration rate system and initial weight

3.2 Normalization of parameters

The results are listed in Table 7.

Table 7: Normalized values of parameters

Component			Beam 1	Beam 2	Column 1	Column 2	Column 3	Column 4
DDS	Qualitative	Overall Appearance	0.12	0.18	0.24	0.28	0.22	0.18
	Quantitative	Crack Width (mm)	0.15	0.20	0.35	0.40	0.45	0.35
		Percentage of Steel Corrosion (%)	0.22	0.24	0.32	0.36	0.24	0.20
		Percentage of Concrete Deterioration(%)	0.15	0.20	0.25	0.25	0.20	0.20
DRS	Qualitative	Environmental Condition	0.28	0.32	0.40	0.40	0.28	0.26
	Quantitative	Steel Corrosion Rate (%/year)	0.10	0.14	0.24	0.28	0.18	0.12
		Deterioration Rate of Concrete Strength (%/year)	0.30	0.40	0.50	0.50	0.40	0.36

3.3 Assessment Results

The assessment results are shown in Table 8.

Table 8: Assessment results of components and frame

Component		Beam 1	Beam 2	Column 1	Column 2	Column 3	Column 4
DDS	Final Weight	0.1952	0.1978	0.1526	0.1544	0.1512	0.1489
	Component Assessment Value	0.3778	0.3888	0.4148	0.4262	0.4057	0.3921
	Frame Assessment Value	0.3995					
	Equivalent Normalized Value	0.2484					
DRS	Final Weight	0.1949	0.1992	0.1545	0.1551	0.1491	0.1471
	Component Assessment Value	0.3941	0.4138	0.4470	0.4513	0.4119	0.3999
	Frame Assessment Value	0.4186					
	Equivalent Normalized Value	0.3055					

3.4 Analysis results

(1) From Table 8, it is seen that deterioration degrees of components are in the following order:
Beam 1∠Beam 2
Column 4∠Column 3∠Column 1∠Column 2

(2) From Table 8, it is seen that deterioration rates of components are in the following order:
Beam 1∠Beam 2
Column 4∠Column 3∠Column 1∠Column 2

(3) Equivalent normalized DD value of frame is 0.2484. This indicates present DD of the frame has reached 24.84% of the tolerable DD. Load carrying capacity of the frame has decreased by 24.84%×10%=2.48%.

(4) Equivalent normalized DR value of frame is 0.3055. This indicates present DR of the frame is 30.55% of the tolerable DR, i.e. present decreasing rate of load carrying capacity is 30.55%×1%=0.306%/year.

(5) From equations (11)(12), we have a =0.0146, b =1.234. Then from equation (13), the residual service life of the frame is determined as 21 years.

4 Conclusions

By now we have established a systematic durability assessment approach for reinforced concrete structures. This approach provides a fair and objective way for analyzing and dealing with data collected by field inspection. The advantages of the approach lie in treating durability of a structure as two multi-hierarchical systems and combining experts' grading with parameters' entropy. By carrying out DDA and DRA, we can obtain more information, such as present structural performance and residual service life. Though the proposed approach takes quite a few steps, yet it is easy to be programmed.

5 References

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