A Method of the Durability Life Prediction for Chinese Historical Reinforced Concrete Structure

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Abstract. In order to evaluate the durability of historical reinforced concrete buildings with square rebars more accurately, a calculation method of durability life for this type of buildings is proposed in this paper. The method mainly includes structural component importance analysis and the calculation method of the durability life prediction for single concrete component with square rebars. Compared with the existing durability evaluation standards and methods based on round rebars, this method is closer to the actual structure status. The works of the paper can be used for the durability evaluation of square steel reinforced concrete buildings and provide a reference for its repair and protection.

1. Introduction

The structural durability is one of the most important problems for reinforced concrete (RC) structures, mainly including durability design, durability protection and durability evaluation. It is hard to create an accurate and unified evaluation method or system for the durability evaluation of RC structures, especially for those buildings built before the 1950s. These early concrete buildings were built before the creation of the matured standards for durability design; thus, it is more difficult to finish the durability evaluation works on them accurately. For example, in China, the first RC building was constructed in the 1900s, but the concrete design standards based on structural reliability were published in the 1980s [1, 2]. Then, a matured durability design standard for concrete structures was published in 2008 [3]. In 2019, the latest standard for durability assessment of existing concrete structures was published [4], which was on the basis of the other current design standards for concrete structures. However, almost all of the concrete structures built before the 1980s cannot meet the requirements of this system now, and the system is probably more inaccurate for those historical RC buildings which have been used for over 60 years. The main reasons are as following:

(1) The durability evaluation method from the current standard is on the basis of “designed service life” which is depended on the current durability design standards [4]. However, there was no concept of “designed service life” for the historical RC buildings, so the calculation method cannot be used directly for these old buildings.

(2) Compared with the presented industry level, the old materials’ properties and construction techniques then were far lower, thus, these historical RC buildings cannot meet the durability design requirements from current standards.

(3) A large number of historical RC buildings used square rebars as stressed rebars in the US [5], UK [6], and China [7]. The square rebar is different from round rebar in the rebar-concrete bond-slip property and corrosion-induced concrete cracking [8], however, the current design and assessment methods for concrete structures are all from the round rebar’s model and experiments [9-12].
The research target in this paper is the historical RC buildings which used square rebars. The research about this type of RC buildings is scanty, mainly on materials properties [7] and comparison on design theories [13]. Besides, Chun and Pan [14] proposed the calculation methods of carbonization life and corrosion-induced cracking life for this type of buildings, but the basic model was still from round rebars’ experiments. Dong et al. [15] carried out a corrosion-induced concrete cracking experiment for square rebar components, analyzing the corrode products of the historical square rebars and the ratio of the critical depth and the section length of the rebars, but no applicable calculation methods. At present, there is no evaluation method for square reinforcement concrete historical buildings. In this paper, a durability evaluation method for square reinforcement concrete buildings is proposed, which can be used for the prediction and assessment of the durability life for this type of buildings.

2. The Assessment Method
The assessment method is mainly composed of three parts of this method: the on-site survey and tests, the structural component importance analysis, and the durability life prediction for critical concrete components. The on-site survey and tests mainly include structural survey and materials tests, which provide the necessary information for calculation. The structural component importance analysis makes the durability life evaluation promote from component level to structure level, and it is achieved by the finite element method. The critical components of the whole structure are obtained from the structural component analysis, and the durability lives of these components are calculated according to a published predicated method for the square rebar case. Then, the weighted average for the durability life of every critical component is calculated, indicating the durability life for the whole structure. The main process of the durability assessment is as figure 1.

![Figure 1. The process of the durability assessment for historical RC buildings.](image1)

![Figure 2. The process of the structural component importance analysis.](image2)

2.1. The Structural Components Importance Analysis
The structural components importance analysis is based on the energy analysis and finite element calculation. The elastic modulus of the component is changed to be nearly zero (0.05% of the original elastic modulus of the material), and each component is traversed. Thus, the effect degree of every component for the strain energy of the whole structure is calculated, and the importance of every
component is obtained. The process of the structural component importance analysis is shown in figure 2. The index of the component importance was defined as the change ratio of the structural generalized stiffness (structural strain energy) caused by component changes (the change of the elastic modulus) [16], and the simplified expression is as following:

$$I = 1 - \frac{K_f}{K_0} = 1 - \frac{U_f}{U_0}$$

(1)

where, the strain $K_0$ and $K_f$ are the generalized stiffness of the original structure and the changed structure, respectively; $U_0$ and $U_f$ are the total strain energy of the original structure and the changed structure, respectively.

In this paper, the calculation is achieved by the finite element model, so one component is composed of many elements. The expression should be as following:

$$\Gamma = \left(1 - \frac{U_0}{U_f}\right) / V_e$$

(2)

where, $\Gamma$ is the unit volume change rate of the total strain energy of the structure, and $V_e$ is the element volume.

2.2. The Durability Life Prediction for Concrete Components with Square Rebars

Due to the poor properties of the old concrete and steel rebars, it is reasonable and conservative to take the corrosion-induced cracking life as the durability life for the square reinforcement historical buildings. The corrosion-induced cracking life of the concrete component includes two periods: the time before rebar corrosion and the time of the corrosion-induced concrete cracking. The calculation method is from the published works of the authors [8] and the Chinese standard [4].

2.2.1. The Time Before Rebar Corrosion. The time before rebar corrosion is based on the concrete carbonization life, and a parameter, carbonation residue $x_0$ was induced for the promotion of the accuracy as that the rebar started corrosion before the carbonization reaching the surface of the rebar in many cases [4]. The calculation equations for the time before rebar corrosion [8] are as following:

$$t_i = \left(\frac{c - x_0}{k}\right)^2$$

(3)

$$x_0 = (1.2 - 0.35k^{0.5}) \cdot \lambda_c \cdot \frac{6.0}{m + 1.6} (1.5 + 0.84k)$$

(4)

$$k = 3.48K_{kl}K_{co2}K_{kt}K_{ks}T^{1/4} (1 - RH) \times RH^{1.5} \left(\frac{58}{f_{cu,e}} - 0.76\right)$$

(5.1)

$$k = \frac{x_c}{\sqrt{t_0}}$$

(5.2)

where $t_i$ is the time before steel rebar corrosion (a); $c$ is the cover depth (mm); $k$ is the carbonization factor; $\lambda_c$ is an influencing factor due to cover depth and carbonization; $m$ is a local environmental factor; $K_{kl}$ is the location factor; $K_{co2}$ is the CO$_2$ density factor; $K_{kt}$ is the construction factor; $K_{ks}$ is the working factor; RH is the environment humidity (%); $T$ is the environment temperature (°C); $f_{cu,e}$ is the estimated value of concrete compressive strength (MPa); $x_c$ is the measured carbonization depth (mm); $t_0$ is the service time of the structure until the on-site test (a).
2.2.2. The Time of the Corrosion-Induced Concrete Cracking. The critical time of the cover cracking due to corrosion is depended on the critical corrosion depth of the rebar and the rate of corrosion. The calculation equations for the time of the corrosion-induced concrete cracking [8] are as following:

\[
t_{cr} = t_{i} + \frac{\delta_{cr}^c}{\lambda}
\]

(6)

\[
\lambda = 5.92K_{cl} (0.75 + 0.0125T)(RH - 0.5) \left( \frac{c}{e} \right)^{0.675} f_{ct, e}^{-1.8}
\]

(7)

\[
\delta_{cr}^c = 0.0409c / d' + 0.0088f_{tk} - 0.0348
\]

(8)

where \(\delta_{cr}^c\) is the critical corrosion of rebar (mm), \(\lambda\) is the rate of rebar corrosion (mm/a), \(K_{cl}\) is the rebar location coefficient, \(d'\) is the width of the square-section rebar, \(f_{tk}\) is the tensile strength of concrete (MPa), and \(t_{cr}\) is the durability life (a).

3. Case Study

A durability assessment of historical concrete buildings with square rebars is studied in this section, which is taken as an analysis case. The building was built in 1934. After the second world war in China, it was rebuilt in 1947, which has been as the provincial protected historical building in Nanjing, China. The structure is a two-story reinforced concrete frame. The plan of the building is square, and the double-eaves pyramidal roof imitated the style of traditional Chinese timber buildings. The south façade of the buildings is shown in figure 3. According to the on-site survey, the tensile rebars are square-section. Figure 4 shows the picture of square rebars.

![Figure 3](image1.png)

**Figure 3.** The south façade of the case building. **Figure 4.** The picture of the historical square rebars.

According to the on-site survey and materials tests, the finite model was created on the finite element calculation software ANSYS (17.0), which is shown in figure 5. In the vertical loading condition, the results of the structural components importance analysis were shown in figure 6. For this structure, the critical components were the four frame columns around the inner square on the plan view (red bar charts in figure 6). The compressive strengths of these four critical concrete columns were tested, obtaining the average strength was 14.0MPa; and according to the working condition, the \(K_{kl}, K_{ks}, RH, T\), and \(K_{cl}\) were determined [4]. Then, the durability life of the historical concrete building was calculated as 72 years. Besides, for comparison, predicted durability lives from three calculation methods based on round rebar experiments were 65 years, 55 years, and 63 years. Table 1 lists the three critical corrosion depth calculation methods for round rebars.
Figure 5. The finite element model of the case building.

Figure 6. The structural components importance results of the building.

An on-site structural assessment and test were finished in 2012 by the author, and the building had been used for 65 years at that time. The inner four critical concrete columns were in a relatively good condition then, and a short corrosion-induced cover cracking appeared on one column locally. According to the on-site assessment then, it can be thought that the proposed method in this paper is more suitable for the durability life prediction for the square reinforcement concrete historical buildings, while the other methods based on round rebars are too conservative.

Table 1. The critical corrosion depth calculation methods for round rebars.

| Source                     | Calculation methods                                      |
|---------------------------|----------------------------------------------------------|
| Chinese standard [4]      | $\delta_{cr} = 0.012 c / d + 0.00084 f_{ch,d} + 0.018$  |
| Rodriguez et al. [17]     | $\delta_{cr} = 0.0074 c / d - 0.0226 f_{ch} + 0.0838$   |
| Webster and Clark [18]    | $\delta_{cr} = 0.00125 c$                               |

4. Conclusion

Many historical RC buildings used square rebars, however, all the current assessment methods and standards are based on the research and experiments on round rebars, which are not suitable for these buildings. In this paper, a method for durability life prediction of historical square reinforcement concrete buildings is proposed, which is based on the structural component analysis and the experimental studies for square rebars. This method is closer to the real condition of these structures than the durability life prediction models for round rebars, and it improves the accuracy of the durability assessment of historical square reinforcement concrete buildings.
Acknowledgments
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References
[1] Ministry of Housing and Urban-Rural Development of the People's Republic of China 1989 Concrete Structure Design Standard GBJ10-89 Beijing: China Architecture Publishing & Media Co., Ltd.
[2] China Academy of Building Research 1984 Unified Standard for Design of Building Structures GBJ68-84 Beijing: China Architecture Publishing & Media Co., Ltd.
[3] Ministry of Housing and Urban-Rural Development of the People's Republic of China 2008 Code for Durability Design of Concrete Structures GBT 50476-2008 Beijing: China Architecture Publishing & Media Co., Ltd.
[4] Ministry of Housing and Urban-Rural Development of the People's Republic of China 2019 Standard for durability assessment of existing concrete structures GBT51355-2019 Beijing: China Architecture Publishing & Media Co., Ltd.
[5] Alexander N 2000 Structural Renovation of Buildings: Methods, Details, & Design Examples (US: McGraw-Hill Professional)
[6] Havel G 2016 Construction Concerns: Concrete Reinforcing Steel. (https://www.fireengineering.com/2016/08/22/289985/construction-concerns-concrete-reinforcing-steel/)
[7] Chun Q, Koenraad V B, and Pan J W 2015 Experimental research on physical and mechanical performance of steel rebars in Chinese modern reinforced concrete buildings built during the Republic of China era from 1912 to 1949 Materials and Structures 49(9) 3679-3692.
[8] Jin H, Chun Q and Hua Y W 2020 Life prediction method on corrosion-induced crack of historical reinforced concrete buildings built in the Republic of China Journal of Southeast University (Natural Science Edition) 50(05) 797-802.
[9] Bazant Z P 1979 Physical model for steel corrosion in concrete sea structures - theory Journal of the Structural Division 105(6) 1137-1153.
[10] El Maaddawy T and Soudki K 2007 A model for prediction of time from corrosion initiation to corrosion cracking Cement and Concrete Composites 29(3) 168-175.
[11] Bilek V, et al. 2017 Bond strength between reinforcing steel and different types of concrete Procedia Engineering 190 243-247.
[12] Liu X, et al. 2020 Bond-slip properties between lightweight aggregate concrete and rebar Construction and Building Materials 255 119335.
[13] Chun Q, Koenraad V B, and Han Y D 2015 Comparison study on calculation methods of bending behavior of Chinese reinforced concrete beams from 1912 to 1949 Journal of Southeast University (English Edition) 31(4) 529-534.
[14] Chun Q and Pan J W 2014 Research on the methods for calculation and prediction of the service life of reinforced concrete buildings built during the period of the Republic of China in Jiangsu and Zhejiang provinces Sciences of Conservation and Archaeology 26(01) 29-33.
[15] Dong Y H, et al. 2017 Critical corrosion depth of rebar of Republican Period reinforced concrete structures Journal of Zhejiang University (Engineering Science) 51(01) 27-37.
[16] Ye L P, et al. 2010 Evaluating method of element importance of structural system based on generalized structural stiffness Journal of Architecture and Civil Engineering 27(01) 1-6.
[17] Rodriguez J, et al. 1996 Corrosion of reinforcement and service life of concrete structures Durability of Building Materials and Components 1: 117-126
[18] Webster M and Clark L A 2000 The structural effects of corrosion - an overview of the mechanisms Conference: Concrete Communications Conference at University of Birmingham.