ASSESSMENT METHOD OF SEISMIC PERFORMANCE FOR CORRODED REINFORCED CONCRETE BUILDINGS

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ABSTRACT

The effects of corrosion of reinforcing steel bars by chloride ingress are seldom considered in mechanical models of shear and flexural capacity for an RC beam or column. That is, seismic capacity or how seismic capacity decreases over time remains unknown. Therefore, this work identifies corrosion-induced weight loss for reinforcing steel bars embedded in concrete. Additionally, an estimating procedure is developed such that structural engineers can evaluate the seismic performance of a deteriorating RC building. Finally, this work adopts an elementary school on Lanyu Island, Taitung, Taiwan, as an example and identifies its time-dependent seismic performance.

Keywords: Seismic performance, Reinforced Concrete, Corrosion, Deterioration, Pushover.

1. INTRODUCTION

Generally, seismic performance of an RC building can be assessed using the capacity spectrum method suggested by the Applied Technology Council (ATC-40 (1996)). By increasing a building's structural strength or ductility, or both, its seismic performance can meet or exceed existing seismic design codes. A structural retrofit of a building improves its capacity to resist seismic events. However, since Taiwan is an island, many RC buildings near the coastline suffer chloride ingress. The safety and serviceability of such structures are decreasing over time. For a deteriorating RC building, even when its seismic performance meets code specifications in one seismic diagnosis, it will decease and may become insufficient over time. That is, corrosion of reinforcing steel bars in RC buildings may decrease their structural integrity under earthquake excitation or even service loads. Therefore, for both economical and safety issues, maintenance plans need time-dependent deterioration models, including repair and retrofitting work, to prevent serious damage to RC buildings. An assessment method is needed that can quantify corrosion-induced weight losses of RC members and evaluate the seismic performance of a deteriorating RC building. The effects of corrosion of reinforcing steel bars by chloride ingress are seldom considered in mechanical models

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of shear and flexural capacity for an RC beam or column. That is, seismic capacity or how seismic capacity decreases over time remains unknown. Therefore, the main purpose of this paper is to develop an estimating procedure based on the static nonlinear pushover analysis (pushover analysis) such that structural engineers can evaluate the seismic performance of a deteriorating RC building. Additionally, for engineers' convenience, this paper suggests the probabilistic deterioration prediction model and the visual estimation of deterioration degree according to the width of cracks in concrete cover to evaluate corrosion-induced weight loss of reinforcing steel bars. Finally, this paper adopts an elementary school on Lanyu Island, Taitung, Taiwan, as an example and identifies its time-dependent seismic performance.

2. EVALUATION METHOD OF CORROSION-INDUCED WEIGHT LOSS OF REINFORCING STEEL BARS

2.1. Probabilistic model for chloride-induced deterioration

Deterioration of an RC building, which leads to corrosion of reinforcing steel bars, is primarily caused by chloride ingress or carbonation. This paper only focuses on the chloride-induced corrosion (Tottori *et al.* (2004)) (Fig. 1). To predict the corrosion-induced weight loss of reinforcing steel bars, besides of the corrosion rate (propagation and acceleration stages), the time required for chloride to corrode reinforcing steel bars (initiation stage) must be simulated using equations that estimate the airborne chloride concentration, the chloride concentration on concrete surfaces, and the diffusion of chloride ions.

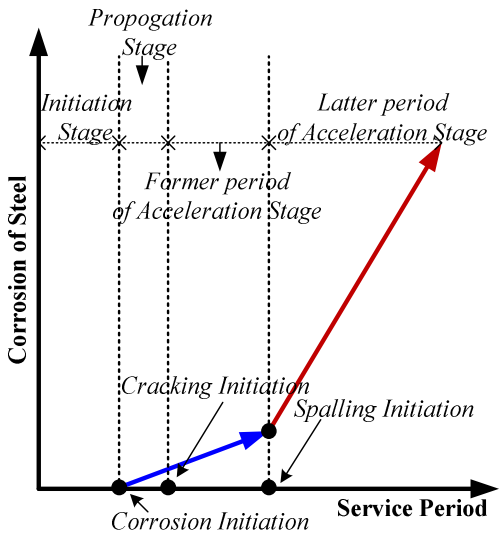


Figure 1 Deterioration process induced by chloride ingress.

Based on observation results obtained by Kato and Uomoto (2005), we assume corrosion initiates when the chloride concentration on the surface of reinforcing steel bars reaches a threshold, which is a random variable distributed uniformly in the range of 1.0 – 1.2 kg/m^3. This paper accounts for uncertainties in chloride-induced deterioration analysis of this stage that are related to

the apparent diffusion coefficient, concrete-cover thickness, and the chloride concentration on concrete surfaces caused by environmental and construction conditions (JSCE (2008)). When corrosion probability that can be calculated using MCS reaches 10 % (ASTM C876 (1991)), this time point is regarded as corrosion initiation (Chiu and Chi (2012)). Based on an existing deterioration model (Takahashi *et al.* (2005)), we assume the rate of corrosion (mg/cm^2/year) in the propagation stage is treated as a lognormal random variable with a mean value, which can be derived using Eq. (1), and a coefficient of variation of 0.5. The effect of corrosion on material degradation is assessed according to the degree of corrosion of reinforcing steel bars, where weight loss is typically used as a quantifiable measure, as in Eq. (2).

$$V_{corr} = \frac{78}{\sqrt{c}}\left(0.578 \times Cl + 0.023(w/c) - 1.52\right) \tag{1}$$

$$\Delta W_{avg} = \frac{4V_{corr}}{\gamma \times d_{bi}} \tag{2}$$

where γ is the density of reinforcing steel bars (mg/cm^3; approximately 7850) and d_{bi} is the diameter of reinforcing steel bars (mm).

According to the Architecture Institute of Japan (AIJ) (AIJ (1997)), spalling of a concrete cover is caused by the formation of cracks with widths exceeding 0.5 – 1.0 mm. The corresponding initiation threshold of the latter period of acceleration stage is difficult to define. In this paper, the empirical result obtained by (Izawa and Matusima (2004)) is used to set the threshold as the weight loss percentage of corroded reinforcing steel of 3.28 %, which is treated as a lognormal distribution with 0.26 as the coefficient of variation. To consider the effects of environmental conditions on the corrosion rate of reinforcing steel bars, this paper uses data for the corrosion rate of carbon steel exposed to air at all test points along measurement lines on the basis of the references (Niu (2003)). Based on the research conducted by Niu (2003) for building the estimation equation for the corrosion rate of reinforcing steel exposed to air, we excluded concrete-cover thickness from the factors (Table 1). Referring to the above deterioration model for chloride-induced corrosion, corrosion curves of reinforcing steel bars, which show the relationship between mean weight loss and time, can be plotted to estimate degradation of the material properties of reinforcing steel bars.

Table 1 Regression equations for the corrosion rate of carbon steel for the coastal regions in Taiwan

Division Zone	Measurement Line	V_{crack} (mm/year)	Mean value of model error	COV of model error
Northern	Suao	$V_{crack} = e^{-0.0809T} \times (RH - 0.45)^{0.2288} \times d^{-0.0374}$	1.13	0.58
Middle	Taichung	$V_{crack} = e^{-0.0513T} \times (RH - 0.45)^{0.938} \times d^{-0.0522}$	1.31	0.73
Southern	Kaohsiung	$V_{crack} = e^{-0.0169T} \times (RH - 0.45)^{1.765} \times d^{-0.0601}$	1.03	0.50
Eastern	Hualien	$V_{crack} = e^{-0.0934T} \times (RH - 0.45)^{0.28} \times d^{-0.0875}$	0.92	0.30

T：mean value of temperature (°C)，RH：mean value of humidity (%)，d：distance to the coastline (km)

2.2. Deterioration degree determined by visual estimation

In addition to the deterioration model, which can predict corrosion-induced weight loss for reinforcing steel bars, this paper uses the guidelines of the AIJ (AIJ (1997)) to investigate and diagnose the durability of RC buildings to estimate corrosion-induced weight loss of reinforcing steel bars using the visual estimation method for deterioration of an RC beam or column. The AIJ's guidelines (AIJ (1997)) have five degrees of corrosion and four degrees of deterioration of a member (Table 2). Table 3 lists the criteria for visual estimation of deterioration degree, including non-, minor, moderate and severe deterioration, which are mainly based on the width of cracks in concrete cover. However, the cracking of concrete cover in a member occurs for various reasons. Therefore, the cause of member cracking must be identified before determining the deterioration degree. However, when a member is slightly deteriorated, removing its concrete cover to assess visually reinforcement corrosion degree is impossible. This paper mainly determines deterioration degree based on the appearance of a member's concrete cover.

Table 2 Evaluation criteria for the degree of corrosion of reinforcing steel bars

Degree of corrosion	Evaluation criteria	Weight loss
Grade I	No corrosion or only dotted rust	< 0.5 %
Grade II	Extensive-dotted rust on surface	0.5 – 1.0 %
Grade III	Dotted rust becomes surface rust, some rust floats.	1.0 – 3.0 %
Grade IV	Rust floats extensively and product from corrosion of reinforcing steel bars is attached to concrete; corroded area of reinforcing steel is less than 20%.	3.0 – 5.0 %
Grade V	Extensive thick-layered rust; corroded area of reinforcing steel exceeds 20%.	> 5.0 %

Table 3 Evaluation criteria for the degree of degradation

Degree of degradation	Evaluation criteria	
	Cracking of concrete surfaces	Corrosion of Reinforcing steel bars
Non-deterioration	No obvious degradation	Corrosion degree of reinforcing steel bars is smaller than II
Minor	No cracks along reinforcing steel bars; width of crack caused by shrinkage is smaller than 0.3mm. Dotted rust can be seen.	Corrosion degree of reinforcing steel bars is III
Moderate	Width of crack caused by corrosion is smaller than 0.5mm	Corrosion degree of reinforcing steel bars is IV
Severe	Width of crack caused by corrosion exceeds 0.5mm, and concrete spalling or floating, reinforcing steel bars exposed to air, etc.	Corrosion degree of reinforcing steel bars is V
		Corrosion degree of reinforcing steel bars is not V, but corrosion degree of most reinforcing steel bars is IV.

3. PLASTIC HINGE PROPERTIES OF A CORRODED RC MEMBER

3.1. Degradation of flexural and shear capacity of RC members caused by corrosion

Reduction in the shear and flexural capacity of a corroded RC beam or column is addressed when investigating the seismic performance. Instead of corrosion reducing the area of reinforcement, a decrease in its material properties, i.e., the yielding stress and modulus of elasticity for steel, and ultimate bonding stress between steel and concrete (Kim *et al.* (2008)), are used to modify the plastic hinge properties for a corroded RC column or beam, which is needed in the nonlinear static structural analysis. The reduction in the flexural capacity of RC members can be caused by the yielding of main bars, and can also be calculated on based on bonding failure between the main bars and concrete after evaluating ultimate bonding stress. Because the bonding failure is a non-warning failure pattern as the shear failure, it is regarded as a shear capacity related to the flexural-bonding failure herein (Chiu and Chi (2012)). The flexural capacity of RC beams or columns caused by the yielding of main bars for any corrosion level, M_{yn}, can also be estimated using the method stated in Chiu and Chi (2012). In this paper, for an RC column or beam with a double curvature, its shear force corresponding to the flexural capacity, V_b, can be estimated. The shear capacity of a corroded RC beam or column can be estimated using the truss-arch theory and mechanical properties of corroded reinforcing steel bars (Chiu and Chi (2012)). According to the research conducted by Chiu and Chi (2012), in addition to the the shear capacity under the stirrup yielding, V_{yn}, the shear capacity in the case of bonding failure, V_{bn}, can be considered as two items according to the truss-arch theory. In this paper, the minimal value of shear capacities corresponding to the stirrup yielding, bonding failure, and flexural-bonding failure is regarded as the shear capacity of a beam or column, V_n.

3.2. Experiment with full-Size corroded RC beams

The experimental result for full-size beams with corroded stirrups (Ou and Chen (2011)) was compared with the prediction result obtained from the models stated above (Fig. 2). Although the mechanical analysis model for corroded components, as proposed in this paper, cannot precisely predict the experimental result (Fig. 2), conservative mechanical properties after reinforcement corrosion can be obtained.

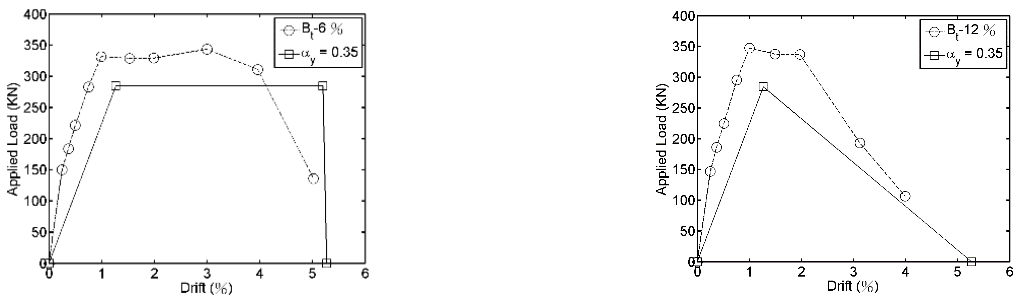


Figure 2 Experiment and analytical results of full-size corroded RC beams.

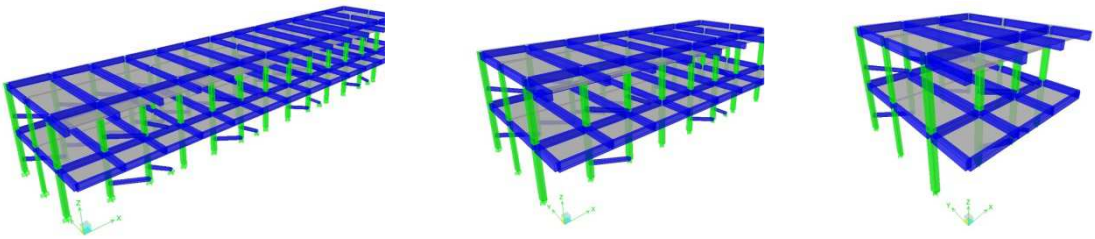
3.3. Modified plastic hinge properties for corroded RC members

The accuracy of pushover analysis depends on the well-defined plastic hinges of each structural element. This paper refers to the method proposed by the National Center for Research on Earthquake Engineering (NCREE-09-023, 2009) for calculating plastic hinge properties for RC members. The failure models of beams or column are identified by the NCREE (NCREE-09-023, 2009). According to the difference between the flexural capacity and shear capacity, the failure modes of a beam or column can be divided into flexural, flexure-shear, and shear failures. For a corroded RC beam or column, the reduction coefficients of plastic hinge properties are defined according to evaluation models for mechanical behavior before and after corrosion. These reduction coefficients are combined with the current and extensively used seismic evaluation procedure by the NCREE (NCREE-09-023, 2009) for engineering convenience.

4. CASE STUDY

The case study is an elementary school on Lanyu Island, located in the eastern side of Taiwan. It has three buildings, named by North Building, Central Building, and South Building, which were constructed in different years (Table 5). The deterioration of these three buildings is evaluated using the probabilistic deterioration prediction model and visual estimation of deterioration degree, as stated in Section 2, respectively. Additionally, to assess their lifetime seismic performance while considering the corrosion effect, plastic hinge properties are modified according to reinforcement corrosion of column members in each building.

The plastic hinge properties of deteriorating column members in the target buildings are modified on the basis of corrosion-induced weight losses. The seismic performance evaluation method proposed by the NCREE is then used to assess the seismic performance of these buildings while using the modified plastic hinge properties. Figure 3 shows the structural models of the buildings, which are needed for seismic performance evaluation. In addition to the probabilistic deterioration prediction model and visual estimation of deterioration degree, the average weight losses of 10.0 % and 20.0 % are also assumed for cases with the severe corrosion. In addition to Fig. 18 of the pushover analysis results, Figure 4 show seismic performance results of the selected buildings. Taking the north building as an example, when corrosion-induced weight loss is evaluated using the visually estimated deterioration degree, seismic performance decreases to 93.9 % of its original seismic performance. However, its seismic performance decreases to 79.4 % when the probabilistic deterioration prediction model is used to estimate corrosion. Thus, for these case study buildings, the probabilistic deterioration prediction model is more conservative than the visual estimation of deterioration degree.



(a) North Building (b) Central Building (c) South Building

Figure 3 Structural models of the selected buildings.

In scenarios with average weight losses of 10.0 % and 20.0 %, average seismic performance of the buildings decreases to 80.5 % and 64.5 % of their original average seismic performance, respectively. Additionally, Figure 19 shows the relationship between service period and seismic performance of the buildings. According to Taiwan's seismic design code, the ground acceleration of Lanyu Island, A_T, is 0.32 g. Taking the south building as an example, average corrosion-induced weight loss of column members is 7.0 % and its corresponding seismic performance, A_p, is 0.32 g at 20 years, which equals the code design value. That is, seismic performance will be insufficient in the 21st year. Additionally, if the specified service life is 50 years, its seismic performance decreases to about 60.0 % of its original seismic performance; therefore, the corrosion effect on the seismic performance of RC buildings cannot be neglected when planning an appropriate maintenance strategy for an RC building. If a deteriorating RC building is located in an environment with high corrosion hazard, its seismic performance will decrease over time; therefore, its seismic design must consider the corrosion effect, such that its seismic performance meets or exceeds the code within its specified service life.

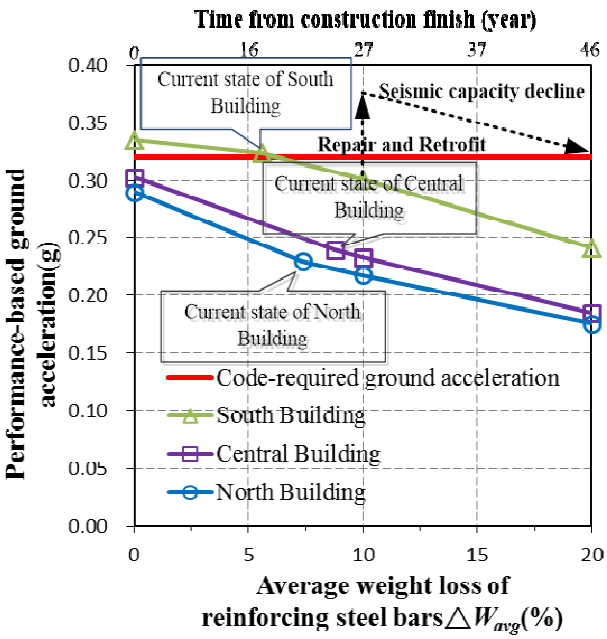


Figure 4 Lifetime seismic performance of the selected buildings.

5. CONCLUSION

This paper incorporates the mechanical models of corroded members into the static nonlinear analysis (pushover analysis) to construct a procedure for assessing the seismic performance of a deteriorating RC building. For engineers' convenience, this paper suggests the probabilistic deterioration prediction model and the visual estimation of deterioration degree to evaluate corrosion-induced weight loss of reinforcing steel bars. Additionally, accurate visual assessments of seismic performance of deteriorating RC buildings require engineers' experience to determine the corrosion degree of reinforcing steel bars and evaluate the seismic performance.

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