

Remaining life assessment of corrosion-affected RC bridge girders using on-line monitoring data

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Abstract

A new approach for remaining life assessment of corrosion-affected reinforced concrete flexural members in the presence of fuzzy and random uncertainties, taking into consideration the delay in detection of corrosion initiation using the on-line monitoring data, is presented in this paper. The approach combines the vertex method with Monte Carlo simulation technique for studying the fuzzy-stochastic evolution of resistance degradation due to chloride-induced corrosion of reinforcement. It is also shown how to determine the bounds for characteristic value of failure probability with minimal computational effort using the proposed approach.

Résumé

Une nouvelle approche pour l'évaluation de la durée de vie restante d'éléments fléchis en béton armé affectés par la corrosion en présence d'incertitudes floues et aléatoires, prenant en compte le retard dans la détection de l'initiation de la corrosion en utilisant les données de surveillance en ligne, est présentée dans cette communication. L'approche combine la méthode vertex avec la technique de simulation de Monte Carlo pour étudier l'évolution stochastique floue de la dégradation de la résistance, du fait de la corrosion de l'armature provoquée par le chlorure. Il est aussi montré comment déterminer les bornes de la valeur caractéristique de la probabilité d'échec avec un effort informatique minimum en utilisant l'approche proposée.

Keywords

Chloride-induced corrosion, reinforced concrete, remaining life assessment, on-line monitoring, hybrid uncertainties.

1 Introduction

Chloride-induced corrosion of reinforcement is an issue of major concern for reinforced concrete structures located in coastal areas. Corrosion of reinforcement is an electrochemical process, and various systems for monitoring of corrosion in the field have been used by different researchers. At present, many of these systems are amenable for on-line corrosion monitoring. There is a need to develop suitable algorithms for timely identification of corrosion initiation from the monitoring data collected by these systems, which will be useful for taking decisions regarding inspection and maintenance scheduling.

An algorithm for identification of chloride-induced corrosion initiation in reinforced concrete structures using on-line monitored corrosion current data was proposed by the authors in their earlier publications [1-2]. Using this algorithm, a new approach for safety assessment of corrosion-affected reinforced concrete flexural members in the presence of

fuzzy and random uncertainties, taking into consideration the delay in identification of corrosion initiation using the on-line monitoring data, is presented. The usefulness of the approach is demonstrated through an example problem of safety assessment of a reinforced concrete bridge girder.

2 Identification of time of corrosion initiation as a change point detection problem

Consider a reinforced concrete member, wherein the corrosion currents are monitored by recording current flow between two identical, electronically isolated, rebar probes, embedded in concrete, and coupled through a zero resistance ammeter (ZRA). At the time of corrosion initiation, t_i , (when depassivation of steel occurs), there is a shift in mean corrosion current, indicating initiation of active corrosion. Thus, the identification of t_i can be viewed as a problem of identifying the time of shift in mean of the monitored corrosion current data, i.e., a change point detection problem [2].

3 Algorithm based on Bayesian approach for identification of time of corrosion initiation

It is assumed that the monitored corrosion current data can be represented using a Gaussian white noise (GWN) process. Balaji Rao *et al.* [1] proposed an algorithm for detecting time of shift in mean amplitude of on-line monitoring data modeled as a GWN process. This algorithm is modified and used for identification of time to corrosion initiation in reinforced concrete structures using electrochemical noise data measured with ZRA technique [2]. The proposed algorithm is based on the work of Fishman [3], where it has been shown that, for all $t \geq 0$, the optimal estimate of the time instant at which a step shift in the mean level of the observed process occurs has the form

$$\hat{\lambda}(t) = \frac{\zeta(t)}{\Lambda(t)} \quad (1)$$

where $\zeta(t)$ and $\Lambda(t)$ are statistics defined by a system of stochastic differential equations. From the simulation studies carried out at, it is noted that there is a need to apply a modification to $\hat{\lambda}(t)$, when $y(t)$ is assumed to be continuously observable in real time. The following decision function is proposed [1]:

$$\lambda(t) = \frac{\left| \int_0^t \hat{\lambda}(x) dx - \hat{\lambda}(t) \cdot t \right|}{|\hat{\lambda}(0) - \hat{\lambda}(t)|} \quad (2)$$

The time of shift is value to which $\lambda(t)$ converges (or when the successive values of $\lambda(t)$ do not differ by more than a specified tolerance).

4 Remaining life assessment

Variations in the estimated remaining life occurs due to the uncertainties in the values of variables used in the modeling of strength and degradation, uncertainties arising due to the description of exposure and quality of construction by linguistic terms, etc. These uncertainties should be taken into account while determining the remaining life of the structural member. Different methods have been proposed by various researchers for handling of fuzzy and random uncertainties together [4-7]. In the present study, a procedure which combines the vertex method with Monte Carlo simulation (MCS) technique is proposed for estimating the remaining life of a corrosion affected RC structural member.

4.1 Procedure for determination of failure probability fuzzy set

In this study, fuzzy-stochastic evolution of resistance degradation is simulated using a hybrid method involving a combination of vertex method [8] and MCS technique. Suppose I_λ is the λ -cut interval, i.e., $I_\lambda = [a, b]$, of fuzzy set A . If fuzzy set B is image of A given by the mapping $B = f(A)$, then interval representing B at a particular value of λ , say B_λ , can be obtained by

$$B_\lambda = f(I_\lambda) = [\min(f(a), f(b)), \max(f(a), f(b))] \quad (3)$$

When the mapping is for n input variables, i.e., $y = f(x_1, x_2, \dots, x_n)$, then

$$B_\lambda = [{}^{\min}_j (f(c_j)), {}^{\max}_j (f(c_j))], \quad j = 1, 2, \dots, N \quad (4)$$

where $N = 2^n$, and c_j represents all possible combinations of input interval variables. In the present study, λ -cut levels are taken as 0^+ , 0.2, 0.4, 0.6, 0.8 and 1.0. For each λ -cut level, possible combinations of the fuzzy variables are considered. Since there are two fuzzy variables (namely, I_{corr} and α), four combinations are possible for each λ -cut level. For each combination, $M_u(t)$ is determined by carrying out a Monte Carlo simulation, by considering width of beam, effective depth of beam, yield strength of steel and compressive strength of concrete as random variables. For each combination, a total of ten thousand samples are used in the simulation, and relative frequency approach is used for determining P_F . From values of P_F for a specific λ -cut level, interval of fuzzy set of P_F is determined. In this way, fuzzy set of P_F at any specific time can be determined.

4.2 Determination of bounds for characteristic value of P_f using possibility theory

Consider a fuzzy set Q with membership function $\mu_Q(x)$. Since the aim is to determine a conservative estimate of the probability of failure (P_F), bounds for a characteristic value corresponding to a high fractile, k (say, 0.95), need to be defined. It has been shown by Savoia [9] that lower bound for characteristic value is given by lower limit of the interval corresponding to λ -cut of fuzzy set Q at k and upper bound is given by upper limit of interval corresponding to λ -cut of fuzzy set Q at $1-k$. Accordingly, from fuzzy sets of P_F at different times, it is possible to determine bounds for characteristic values corresponding to any fractile k (taken as 0.95 in this study since a conservative estimate of P_F is required). The upper bound of the characteristic value is recommended for decision-making purposes.

4.3 Remaining life estimation

The diameter of the reinforcing bar at any time t , after corrosion initiation, is given by,

$$\varphi(t) = \varphi(0) - 0.0115 \alpha i_{corr} (t + t_d) \quad (5)$$

where $\varphi(0)$ and $\varphi(t)$ are diameters of bar before corrosion initiation and at time ' t ', respectively; α is a parameter varying in the range 4 to 8 for pitting type of corrosion; i_{corr} is the corrosion current density; t is the time elapsed after detection of corrosion initiation, and t_d is the delay in detection for the algorithm used for detection of corrosion initiation. Knowing the diameter of the reinforcing bars, cross-sectional dimensions of reinforced concrete member, strengths of steel and concrete, it is possible to estimate the resistance of the member in flexure/shear/torsion at any given time. In the present study, the ultimate moment of resistance at any time ($M_u(t)$) is computed using the relations given in IS 456-2000 [10] without the partial safety factors. $M_u(t)$ is compared with the moment due to service loads (M_{SL}) to determine the P_F and hence the remaining life.

In the present study, λ -cut levels are taken as 0^+ , 0.2, 0.4, 0.6, 0.8 and 1.0. From values of P_F for a specific λ -cut level, interval of fuzzy set of P_F is determined. In this way, fuzzy set of P_F at any specific time is determined, and bounds for characteristic values corresponding to high fractile (taken as 0.95 in this study since a conservative estimate of P_F is required) are determined. The usefulness of the proposed algorithm for identification of corrosion initiation and remaining life assessment is illustrated through an application.

5 Application

A reinforced concrete bridge girder, located in a *severe* environment (as per the definitions of exposure conditions in IS 456-2000 [10]) is considered (more details of the girder are given in Anoop *et al.* [11]). An ensemble of $y(t)$ is generated [12] which is assumed to represent the electrochemical current noise data obtained from on-line monitoring and the stochasticity in time of occurrence of change point event (initiation of chloride-induced corrosion) is taken into consideration as follows. Assuming ingress of chlorides into cover concrete as a diffusion process, time-to-corrosion initiation (t_i) can be determined from Fick's second law of diffusion as

$$t_i = \frac{d^2}{4D} \left[\text{erf}^{-1} \left(\frac{c_s - c_{cr}}{c_s} \right) \right]^2 \quad (7)$$

where d is the clear cover to reinforcement, D is the diffusion coefficient for chlorides in concrete, c_s is the surface chloride concentration and c_{cr} is the critical chloride concentration. To account for variations in workmanship and exposure conditions, d , D , c_s and c_{cr} are treated as random variables. The values of mean and standard deviation of these random variables are given in Table 1. All the random variables are assumed to be statistically uncorrelated with each other. The mean and standard deviation of time-to-corrosion initiation is determined using first order approximation, and it is assumed that t_i follows a lognormal distribution.

Table 1. Random variables considered for determination of t_i

variable	mean	SD	Remarks
d (mm)	45	2.25	cov = 0.05 [13]
D (cm ² /s)	5×10^{-8}	1×10^{-8}	cov = 0.20*
c_s (% by weight of concrete)	0.25	0.05	cov = 0.20*
c_{cr} (% by weight of concrete)	0.125	0.025	cov = 0.20*

(Note: * - assumed)

It is assumed that monitored electrochemical noise data can be represented by a GWN process. One thousand realizations of GWN process are generated representing the possible realizations of monitored electrochemical noise for a period of 100 years at an interval of 0.01 years. One thousand lognormal random variables, representing time-to-corrosion initiation, one for each realization of the observed process, are generated. The time of shift is determined using Eq. 2 for each realization of the process.

Table 2. Random and fuzzy variables considered for remaining life assessment

Variable	Mean	COV	Distribution/ membership function	Reference
Breadth of flange (mm)	2000	0.03	Normal	[14]
Effective depth (mm)	891	0.03	Normal	[14]
Compressive strength of concrete, f_c (N/mm ²)	46.88	0.176	Normal	[13]
Yield strength of steel, f_y	415	0.12	Normal	[13]

(N/mm ²)				
Delay in detection of corrosion initiation (years)	0.14	0.11	Lognormal	(from simulation of this study)
Corrosion current density, I_{corr} ($\mu\text{A}/\text{cm}^2$)	3.5*	2 - 5**	Triangular	[11]
α	4.5 - 6 [#]	4 - 7**	Trapezoidal	[11]

(Note: * - prototypical element, ** - support of the fuzzy set, # - core of the fuzzy set)

The moment due to service loads is considered to be deterministic, and is equal to 711.0 kN-m [11]. The statistical properties of delay in detection are taken as that obtained using the proposed algorithm. The random and the fuzzy variables considered together with their properties are given in Table 2.

6 Results and discussion

From simulation, the mean and standard deviation for delay in detection are obtained as 0.14 and 0.11 years. The small values of delay in detection and error in detection indicate the usefulness of the proposed algorithm. The fuzzy sets of P_F at 15, 30, 45 and 60 years after detection of corrosion initiation are shown in Fig. 3. From this figure, it is noted that interval lengths of fuzzy sets of P_F at a given λ -cut level increase with age, resulting increase in uncertainty about P_F with age. The increase in uncertainty about P_F with age can be attributed to increase in uncertainty about depth of corrosion penetration with increase in time.

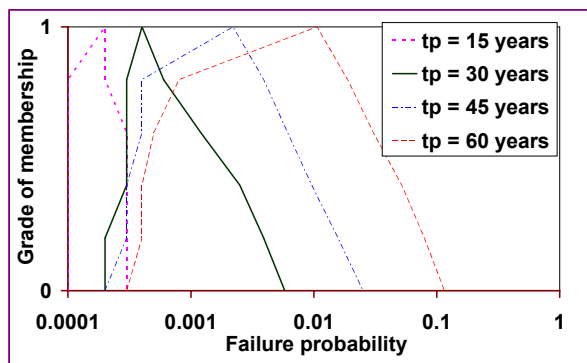


Figure 1. Fuzzy sets for P_F (t_p - years after detection of corrosion initiation)

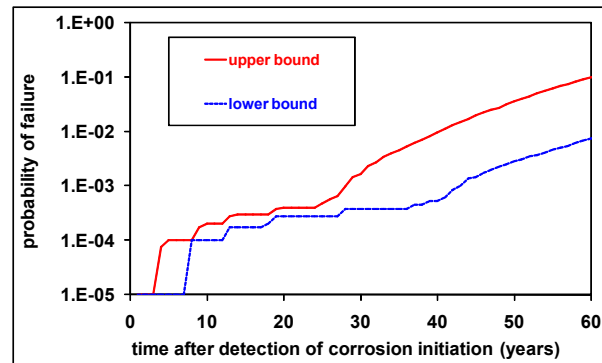


Figure 2. Bounds for characteristic value of failure probability

The P_F values obtained from fuzzy-probabilistic analysis are more rational since appropriate representations of uncertainty are used for the different variables. Also, by carrying out a probabilistic analysis, while it is possible to obtain bounds on P_F , it may be computationally expensive to obtain probability distribution for P_F . But from the resulting fuzzy set of P_F obtained using the proposed procedure, one can obtain not only the possibility distribution of P_F , but also the bounds for characteristic values of P_F corresponding to a specified fractile, with minimal computational effort. The bounds for characteristic values of P_F corresponding to 0.95 fractile obtained from fuzzy sets of P_F at different times are shown in Fig. 4. The upper bound for characteristic value of P_F shown in Fig. 4 can be used for remaining life estimation (by comparing with the allowable value of P_F) and for decision-making regarding in-service inspections.

7 Conclusions

A methodology for remaining life assessment corrosion-affected reinforced concrete flexural members in the presence of fuzzy and random uncertainties, taking into consideration

the delay in detection of corrosion initiation using the on-line monitoring algorithm, is presented. The usefulness of the approach is demonstrated through an example problem of remaining life assessment of a reinforced concrete bridge girder. It is also illustrated that one can determine the bounds for characteristic value of failure probability from the resulting fuzzy set for failure probability with minimal computational effort. The fuzzy-probabilistic approach presented will be useful for remaining life estimation and for making decisions regarding in-service inspections.

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