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ROLE OF IN-SERVICE INSPECTION AND MAINTENANCE IN RELIABILITY ASSURANCE OF CONCRETE STRUCTURES IN NUCLEAR PLANTS

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ABSTRACT

The degradation in strength of a component with random damage is evaluated using a growth model for individual damages which can be obtained from experimental data. The distribution function of damage intensity after inspection and repair is updated using a Bayesian analysis that takes the quality of inspection into account. With this posterior distribution, the time-dependent strength after the inspection and repair can be evaluated. Time-dependent reliability analysis can be used to determine inspection/repair strategies that are necessary to keep the failure probability of the component lower than an established target.

1 INTRODUCTION

The failure probability of a structural component under stationary random loading can be evaluated as a function of time if the degradation function defining the fraction of initial strength remaining at time, t, and the probabilistic characteristics of the initial strength and loads modeled as stochastic processes are known [3]. In order to evaluate the effect of periodic inspection and maintenance on the failure probability of a structure, it is necessary to relate the strength degradation to the damage intensities and to determine the impact of various repair strategies on strength.

2 DEGRADATION FUNCTION BASED ON INDIVIDUAL DAMAGE INTENSITIES

The damage intensity is modeled in the abstract as a state variable taking a value within the interval [0,1]; the values 0 and 1 indicate no damage and no residual strength, respectively. Examples of this state variable would include the ratio of area of reinforcement lost due to corrosion to the original area. The following assumptions are made:

(a) Initiation of damages in a component is described by a Poisson process in which the expected number of damages in time interval $(t, t+\Delta t]$ is $\int_t^{t+\Delta t} \nu(\tau)d\tau$ for $t > 0$. $\nu(w)$ is dependent on the surface area or volume of the component.

(b) Damages initiate homogeneously over the surface area or volume of the component.

(c) Once damage initiates at location j, it grows according to

$$X_j(t) = \begin{cases} 0 & ;0 \leq t < T_{I_j} \\ C_j(t - T_{I_j})^{\alpha} & ;t \geq T_{I_j} \end{cases} \tag{1}$$

in which $X_j(t)$'s are the intensity of damage at time t, T_{I_j}'s are the random times of which damage initiates, C_j's are damage growth rates which are assumed to be identically distributed and statistically independent random variables described by a cdf $F_C(c)$, and α is a deterministic parameter. Parameters C and α depend on the degradation mechanism (e.g., [2]).

(d) The degradation function, $G(t)$, for a component can be given in terms of damage intensities as,

$$G(t) = 1 - \max_{all\, j}\{X_j(t)\} \tag{2}$$

Consider damages which initiate within interval $(t_1, t\,]$. Given that the number of these damages equals n, the rank-ordered initiation times, $T_{I_1}, \ldots, T_{I_n}$ are n order statistics of random variables $W_{I_1}, \ldots, W_{I_n}$ which are statistically independent and identically distributed with pdf expressed as [5],

$$f_{W_I}(w) = \begin{cases} \dfrac{\nu(w)}{\int_{t_1}^{t} \nu(\tau)d\tau} & ; t_1 \le w \le t \\ 0 & ; \text{Otherwise} \end{cases} \tag{3}$$

From assumption (c), the cdf of $X_j(t)$, $F_X(x; t_1, t)$, is expressed as,

$$F_X(x; t_1, t) = \int_{t_1}^{t} F_C\left(\frac{x}{(t-\tau)^{\alpha}}\right) f_{W_I}(\tau)d\tau \tag{4}$$

The cdf of $X_{max}(t_1; t) = \max_j\{X_j(t)$ initiating within $(t_1, t\,]\}$ is expressed as [4],

$$F_{X_{max}}(x; t_1, t) = \exp\left[-\int_{t_1}^{t} \nu(\tau)d\tau\{1 - F_X(x; t_1, t)\}\right] \tag{5}$$

From assumption (d), the mean of the degradation function is evaluated by,

$$E[G(t)] = 1 - \int_0^1 [1 - F_{X_{max}}(x; 0, t)]dx \tag{6}$$

In the course of the analysis, it was found that the variability in $G(t)$ has a secondary effect on the time-dependent reliability of a component, and thus the reliability can be evaluated considering only the mean of $G(t)$, defined as $g(t)$ [4].

3 DEGRADATION FUNCTION AFTER REPAIR

No nondestructive evaluation (NDE) method can detect a given defect with certainty. The imperfect nature of NDE methods must be described in statistical terms. Fig.1 illustrates conceptually the probability, $d(x)$, of detecting a defect of size x. Such a relation exists, at least conceptually, for each in-service inspection technology.

Assume that during inspection/maintenance the entire component is inspected, that all detected damages are repaired immediately and completely, and that the repaired parts of the component are restored to their initial strength levels. Then the effect of inspection/maintenance on $g(t)$ depends on the detectability function, $d(x)$, associated with the NDE method. The inspection with higher $d(x)$ makes repair more likely and, accordingly, leads to higher values of the degradation function, $g(t)$. In the limit, if an inspection is perfect, i.e., $d(x) = 1$ for $x > 0$, then the component is restored to its original condition by the repair.

3.1 Step Detectability Function

Let us first assume that the detectability function, $d(x)$, is defined as

$$d(x) = \begin{cases} 0 & ; \quad 0 \leq x < x_{th} \\ 1 & ; \quad x_{th} \leq x \leq 1 \end{cases} \tag{7}$$

where x_{th} is the minimum detectable value of damage. The same detection threshold values are assumed for all inspections. Following m inspections at $\underline{t}_R = \{t_{R_1}, \ldots, t_{R_m}\}$, some of the damages are repaired and the cdf describing $X(t)$ and the number of damages existing at time $t > t_{R_m}$, $N(t)$, changes. The intensities of damages that initiate after t_{R_m} are independent of repair, and only the pdf of the intensities of damages initiating before t_{R_m} is updated. Let us consider damages which exist at time t and initiate within (A) $(0, t_{R_m}]$ and (B) $(t_{R_m}, t]$. The number of damages left unrepaired after t_{R_m}, $N_{(A)}$, can be described by a filtered Poisson process with a parameter $p \cdot \nu(w)$, where

$$p = P[\text{A damage is not repaired by } t_{R_m}] = F_X(x_{th}, 0, t_{R_m}) \tag{8}$$

while the number of damages initiating within $(t_{R_m}, t]$, $N_{(B)}$, is described by a Poisson process with a parameter $\nu(w)$. In other words, the number of defects existing at time t can be described by a nonstationary Poisson process with a parameter $\nu''(w)$ given by

$$\nu''(w) = \begin{cases} p \cdot \nu(w) & ; 0 < w \leq t_{R_m} \\ \nu(w) & ; t_{R_m} < w \leq t \end{cases} \tag{9}$$

Therefore, the procedure to estimate the degradation function for a component before an inspection/repair discussed in the preceding section can be used to estimate the function after multiple inspection/repair, replacing $\nu(w)$ by $\nu''(w)$, and $F_X(x; 0, t)$ by the updated cdf, $F''_X(x; t_{R_m}, t)$.

By the theorem of total probability, $F''_X(x; t_{R_m}, t)$ can be expressed as,

$$F''_X(x; t_{R_m}, t) = F_{X_{(A)}}(x; t_{R_m}, t) \cdot P(A) + F_{X_{(B)}}(x; t_{R_m}, t) \cdot P(B) \tag{10}$$

in which $F_{X_{(A)}}(x; t_{R_m}, t)$ and $F_{X_{(B)}}(x; t_{R_m}, t)$ are the cdf of intensity of damages in group (A), $X_{(A)}(t)$, and intensity of damages in group (B), $X_{(B)}(t)$, respectively, and $P(A)$ and $P(B)$ are the probabilities that a defect belongs to group (A) or (B):

$$P(A) = P[W_I \leq t_{R_m}] = \int_0^{t_{R_m}} f_{W_I}(w)dw \tag{11}$$

$$P(B) = 1 - P(A) \tag{12}$$

in which $f_{W_I}(w)$ is evaluated by Eqn.(3) replacing $\nu(w)$ with $\nu''(w)$. $F_{X_{(A)}}(x; t_{R_m}, t)$ is expressed as,

$$\begin{aligned} F_{X_{(A)}}(x; t_{R_m}, t) &= P[X(t) < x | X(t_{R_m}) < x_{th}] \\ &= \frac{\displaystyle\int_0^{t_{R_m}} F_C\left(min\left\{\frac{x}{(t-\tau)^\alpha}, \frac{x_{th}}{(t_{R_m} - \tau)^\alpha}\right\}\right) f_{W_I}(\tau)d\tau}{\displaystyle\int_0^{t_{R_m}} F_C\left(\frac{x_{th}}{(t_{R_m} - \tau)^\alpha}\right) f_{W_I}(\tau)d\tau} \end{aligned} \tag{13}$$

The cdf $F_{X_{max(B)}}(x; t)$ is given by

$$F_{X_{(B)}}(x; t) = F_X(x; t_{R_m}, t) \tag{14}$$

3.2 General Detectability Function

In general, the detectability function, $d(x)$, is not a step function but rather a non-decreasing function of damage intensity (see Fig.1). Noting that a detectability function has the same property as a cdf, i.e., non-decreasing and taking a value within $[0,1]$, $d(x)$ can be interpreted as describing an inspection with a step detectability function in which the threshold value, X_{th}, is a random variable with cdf, $F_{X_{th}}(x) = d(x)$. In short,

$$\begin{aligned} d(x) &= P[\text{Detect damage with intensity as small as } x] \\ &= P[X_{th} \leq x] \end{aligned} \tag{15}$$

$F_{X_{th}}(x)$ can be interpreted as the distribution function of the smallest detectable defect size.

The cdf of damage intensity in group (A) after inspection is evaluated as (cf. Eqn.(13)),

$$\begin{aligned} F_{X_{(A)}}(x;t_{R_m},t)dx &= P[X(t) \leq x | X(t_{R_m}) < X_{th}] \\ &= k \cdot \int_0^1 F_{X_{Step}}(x;x_{th}) \cdot F_X(x_{th};0,t_{R_m}) \cdot f_{X_{th}}(x_{th})dx_{th} \end{aligned} \tag{16}$$

in which k is a normalizing constant so that $F_{X_{(A)}}(x;t_{R_m},t)$ is a legitimate cdf, $F_{X_{Step}}(x;x_{th})$ is the cdf of damage intensity for a step detectability function with a threshold value x_{th}, evaluated by Eqn.(13), and

$$f_{X_{th}}(x) = \frac{d}{dx}d(x) \tag{17}$$

The cdf of damage intensity in group (B) after inspection remains unchanged from Eqn.(14).

4 EFFECT OF INSPECTION/REPAIR OPERATIONS ON RELIABILITY

In order to study a simple case, let us assume that:

(a) The initiation of damages is described by a stationary Poisson process with $\nu = 5/\text{yr}$.

(b) Damage grows linearly as a function of time as described by Eqn.(1) with $\alpha = 1$; moderate reinforcement corrosion is typified by such growth [4].

(c) The degradation rate, C, is lognormally distributed with mean values, $\mu_C = 0.00125$, which corresponds to $E[X(40)|T_I = 0] = 0.05$, and with coefficient of variation, $V_C = 0.5$.

The effect on the mean degradation function of inspection/repair described by several detectability functions is illustrated in Fig.2. The first detectability function considered is a step detectability function in which $x_{th} = 0.03$; in the second, X_{th} is uniformly distributed (i.e., $d(x)$ is linear between x_{min} and x_{max}, where $d(x_{min}) = 0$ and $d(x_{max}) = 1$); in the third and fourth, X_{th} is lognormally distributed with mean, $\mu_{X_{th}}$, equal to 0.03, and coefficient of variation, $V_{X_{th}}$, equal to 0.3 or 0.5. It is assumed that inspection/repair is carried out at $t_{R_m} = 20$ years. The mean degradation function decreases as $V_{X_{th}}$ increases (which would result in lower reliability); however, the effect of the general shape of $d(x)$ (Fig.1) is not significant and decreases with time elapsed since inspection. This insensitivity of the mean degradation to the choice of detectability function suggests that a general detectability function might be approximated for practical purposes by a step function with $x_{th} = \mu_{X_{th}}$. This would be advantageous for NDE technologies currently used for reinforced concrete structures because information on $\mu_{X_{th}}$ may be more readily available than information on $d(x)$.

The effect of multiple inspections/repairs on the mean degradation function is illustrated in Fig.3, considering the step detectability function. Inspections/repairs are carried out at 20, 30, 40 and 50 years with $x_{th_j} = x_{th} = 0.05$ or at 30 years with $x_{th} = 0.01$. With multiple inspection/repair, the mean degradation function can be kept within a narrow range during the service life of a structure; the width and the location of the range can be controlled by the frequency and the threshold value of the inspections.

Failure probabilities for a service life of 60 years evaluated with the degradation functions illustrated in Fig.3 are presented in Fig.4 for a reinforced concrete component designed for flexure using the design load combination for dead plus live load in ACI Standard 318 [1],

$$0.9R_n = 1.4D_n + 1.7L_n \tag{18}$$

in which R_n = nominal strength and D_n and L_n = nominal dead and live loads. The probabilistic models of load intensity used in this illustration are summarized in Table 1. It is assumed that the initial strength has a lognormal distribution with $\mu_R = 1.15R_n$ and coefficient of variation (c.o.v.) $V_R = 0.15$ and that $D_n = L_n$. The basis for these load and resistance statistics is given elsewhere [3],[4]. The slope of $F(t)$ changes at the time of repair. The combined effect of multiple repairs with $x_{th} = 0.05$ leads to a failure probability during 60 years that is comparable to that of the single more intensive repair.

5 CONCLUSIONS

Results such as those in Fig.4 suggest the existence of an optimum inspection/maintenance strategy in which the failure probability of the component is kept below an established target probability during its service life and the total expected cost, defined as the sum of the cost of inspections/repairs and the expected loss due to failure, is minimized. The development of such a strategy is presented in detail elsewhere [4]. In situations where the cost of failure dominates the expected total cost, the optimum policy involves inspection/repair at nearly uniform intervals during the service life of the structure.

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Table 1: Load Process Parameters

	Mean*	C.o.v.	Pdf	$\lambda(yr^{-1})$	τ^{**}
Dead Load	$1.00D_n$	0.07	Normal	–	–
Live Load	$0.40L_n$	0.50	Type I	0.5	3 months

*D_n and L_n are nominal loads.

**τ is the mean duration of a load event.

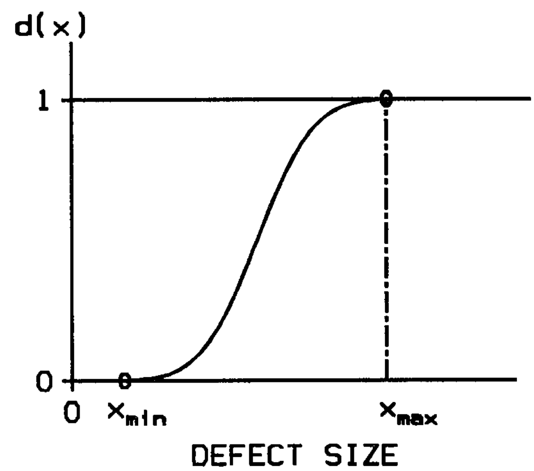

Fig.1: Defect Detectability Function

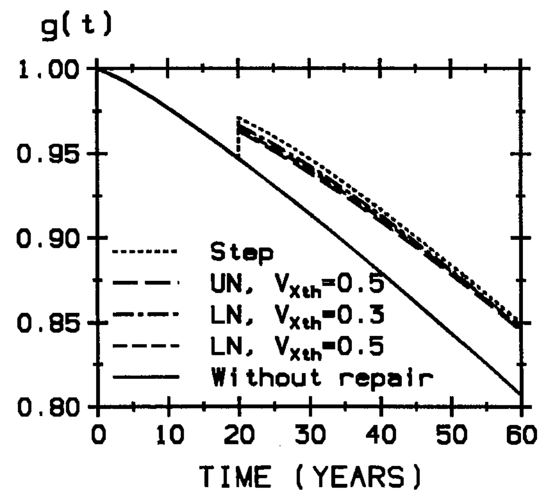

Fig.2: Mean Degradation Function with Repair with General d(x)

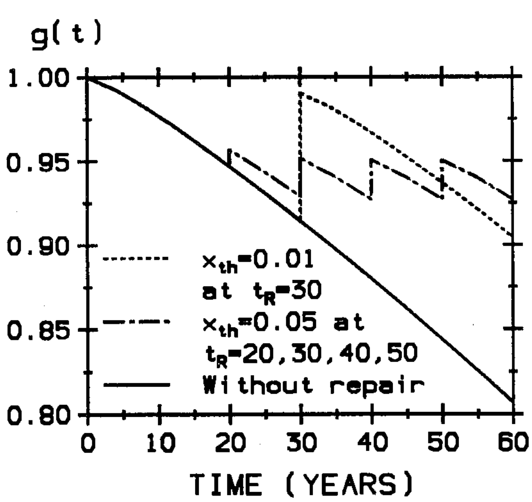

Fig.3: Mean Degradation Function with Multiple Inspection

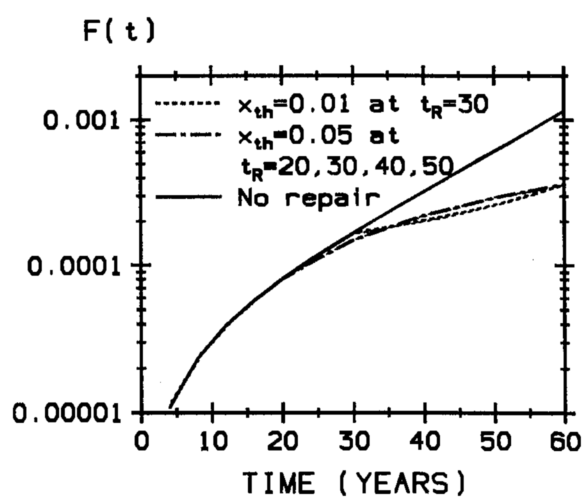

Fig.4: Failure Probability With Multiple Inspection