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Maintenance Strategies for Degrading Structures in NPP's Based on Time-Dependent Reliability Models

Adrian Vulpe and Alexandru Carausu

Technical University of Iasi, Romania

ABSTRACT. The deteriorating / degrading processes affect both structures and equipment in nuclear power plants, but the monitoring of the effects of aging as well as the ways of correcting them have specific features. The degradation in strength of a component with random damage is approached in terms of various models. Time-dependent reliability is essentialy involved in selecting optimum inspection / maintenance strategies able to keep the failure probability of a component or structure below an established target value. We propose a couple of ways to integrate certain methods for reliability assessment and maintenance strategies with models based on damage indices and matrices, state transition probability matrices and seismic vulnerability functionals.

1 INTRODUCTION

The importance of evaluating the reliability of existing structures in NPPs was outlined in the NRC Structural Aging Program and it is also approached in [1] & [2], from the point of view of necessary extensions of plant operating licences. This follows from the substantial shutdown and decomissioning costs of existing old NPPs. A major concern consists in ensuring that the capacity of safety-related systems to withstand extreme events has not too much deteriorated due to structural aging during the previous service history, so that they would be able to reliably withstand during a new service cycle. The damages induced by aging of structures in nuclear plants involves a degradation in strength of structural components. This degradation is evaluated, in [3], together with the role of inspection and maintenance strategies in ensuring a target reliability for a new operating cycle.

Starting from the models and methods presented by B.Ellingwood & Y.Mori in these essential references [1,2,3], we discuss some possible extensions. The concept of *maintenance* has broader or more specific meanings. Basically, it consists just in devising adequate strategies of (in-service) inspection and repair able to preserve the reliability of a structure / system / equipment above a imposed threshold during its service life. Damage indices have got a rather broad use in recent studies [4,5], but mainly for standard structures and less in NPP's. However, we consider the use of such indices as possible, and we propose some ways to integrate them with the analytic models of degradation in [1,2,3], stochastic transition matrices a.o. The physical degradation of a component / structure is a *time-dependent process* whereas the damages are rather momentary attributes, resulting in an overall reliability decay of the system. If the analysis is focused on the effects of ageing, the damages are measurable effects of the degradation process. If the random actions / loads from the environment (like earthquakes) are under the main concern, then the successive damages in a component or structure naturally accelerates the degrading process, and inspection / repair / maintenance strategies are very important for extending the service life of the structure.

2 DEGRADATION FUNCTIONS IN TIME-DEPENDENT RELIABILITY MODELS

For a single structural component, the strength function $R(t)$ and the load effect $S(t)$ are random functions of time and their difference defines the time-dependent margin of safety:

$$M(t) = R(t) - S(t). \tag{1}$$

The general time-dependent evolution of the strength function $R(t)$ can be expressed [1] as $R(t) = R_0 \cdot g(t)$ where R_0 is the initial strength (or - more precisely - the component capacity in the undegraded / original state) and $g(t)$ is the time-dependent degradation function defining the fraction of the initial strength remaining at time t. Certainly, $g(t)$ should be a mono-tonically decreasing function taking values in $[0,1] : g([0,T]) \subseteq [0,1]$, where $T =$ the predicted service time of the component or life time of the structure. Certainly, the function $g(t)$ is no more decreasing (or only piecewise decreasing) when maintenance and repair operations are performed during $(0,T)$. It becomes a discontinuous function of the characteristic shape met for similarly defined functions in renewal processes. The two types of functions are illustrated in the Figure 1 at left. Two types of degradation functions are plotted : $g(t)$ for a continuous degradation process, and $\bar{g}(t)$ for a time history with decays induced by strong loads and followed by repair operations. Such loads are assumed to occur at moments $t_1 < \ldots < t_i < \ldots < t_j < \ldots$ and some of them are followed by repair intervals τ_i if $R_0 \cdot \bar{g}(t_i + \Delta t) \le \gamma$ = a prescribed threshold. The function $\bar{g}(t)$ is assumed to skip at a higher value after a repair operation so that (for instance) $\bar{g}(t_i + \tau_i + \Delta t) \ge 0.9 R_0$.

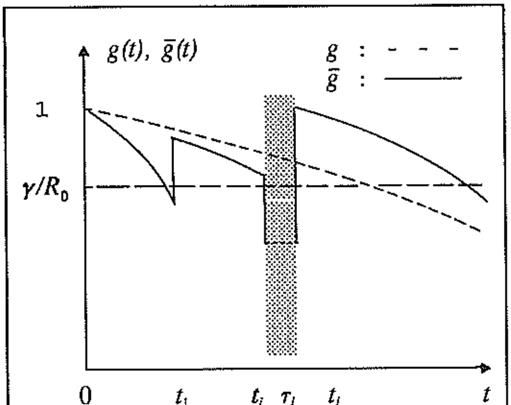

Fig.1 Degradation functions without and with maintenance

Under the usual assumption that R and S are statistically independent, the time-dependent probability of failure is

$$P_f(t) = P[M(t) \le 0] = \int_0^{\infty} F_R(\tau) f_S(\tau)\, d\tau \tag{2}$$

where $F_R(t)$ is the *cdf* of R and $f_S(t)$ is the *pdf* of S.

The time-dependent safety margin in Eq.(1) is not sufficient for describing the degradation process of a component in an existing structure or of the structure itself. Another time-dependent *degradation* function must be introduced, as in (e.g.) [2], in terms of several damage intensity functions assigned to specified locations in the structure (where the damage process is observed and evaluated : $G(t) = 1 - \max_{\text{all } j}\{X_j(t)\}$.

The "local" functions $X_j(t)$ are analytically expressed in terms of n specific damage growth rates C_j whose *cdf* $F_{\mathbf{C}}(\mathbf{c})$, $\mathbf{C} = [C_1 \dots C_j \dots C_p]$. is involved. This model is based on the assumption that the initiation of damages can be described by a Poisson process.

In the next section we shall see how this approach (or similar ones) can be involved in models based on damage state indices for structures subjected to severe ground motions.

3 DAMAGE STATE INDICES AND SEISMIC DAMAGE RISK FUNCTIONALS

Several damage indices have been proposed in literature. When the loading / demand model is focused on earthquake ground motions and their effects, such indices are naturally related to seismic fragility models, that is to the conditional probability of a component / structure to keep its strength capacity under (after) earthquake motions of a certain random intensity. The damage level is discretized (in [4,5]) in terms of a damage state vector $\mathbf{D} = [d_0, d_1, \dots, d_m]$. Its components are assumed to be ordered according to a damage level scale : $d_0 \prec d_1 \prec \dots \prec d_k \prec \dots \prec d_m$.

The earthquake intensity parameter Y (which can be taken as PGA, PGV or intensity class) can also be discretized as $\mathbf{Y} = [y_1, \dots, y_k, \dots, y_n]$ such that its components y_k $(k = \overline{1,n})$ are either discrete points in the range of Y (e.g., centers of earthquake intensity intervals) or intensity classes of earthquakes over a discrete intensity scale.

The damage intensity D can be quantified in several ways. One of them is in terms of a damage index I_D which takes values over an interval

$$[D_L, D_U] = \bigcup_{i=1}^{m} [\ell_i, u_i) \text{ such that } u_i = \ell_{i+1} \text{ and } I_D \in [\ell_i, u_i) \Longleftrightarrow D = d_i . \quad (3)$$

Then the probability of (earthquake induced) damage of a structure to exceed the damage state d_i at a specified level of the ground motion intensity can be expressed as

$$P_{i|k} = P(D \geq d_i \mid Y = y_k) = P(I_D \geq \ell_i \mid Y = y_k) = \sum_{j=i}^{m} P_{j|k} . \quad (4)$$

The probability in Eq.(4) cannot be directly evaluated. In many studies, a damage index is used to quantify the damage level experienced by a structure. This random damage index I_D is a function I of structural (strength) parameters and demand (load) variables. Thus $I_D = I(\mathbf{R}, \mathbf{S})$. In the the model of [5], the demand / load vector and the capacity vector are random scalar functions that respectively depend on the seismic variables $\mathbf{S}$ and on resistance variables $\mathbf{R}$, that is $L = L(\mathbf{S})$ & $C = C(\mathbf{R})$. The damage index I_D is a composed function through these ("synthetic") variables :

$$I_D = I(C, L) = I(C(\mathbf{R}), L(\mathbf{S})) . \quad (5)$$

Each conditional probability as in Eq.(4) results in a fragility curve for damage state d_i. In many references, the set of damage state is "linguistically" stated. For instance, it could be (as in [5]) $\mathbf{D}$ = {**none, minor, moderate, severe, collapse**} . Such a qualitative description of the damage states is customary in the fuzzy approaches, and it gives a suggestion for employing fuzzy models in the reliability evaluation of degrading structures. In terms of the damage state set, this description would result in $\mathbf{D} = [d_0, d_1, d_2, d_3, d_4]$. But even when the approach is not fuzzy but a quantitative evaluation of the damage levels is not available, the necessity of using damage indices becomes evident.

The choice of proper (local and global) damage intensity indices is important, and a large diversity of such damage measures have been proposed in more or less recent references. Naturally, the choice essentially depends on the nature of the structure under analysis as well as on the type of loads the component / structure has to support. One of the widely used index is Park & Ang's index ; it is used in [4,5] for the stochastic seismic estimation and Bayesian updating of fragilities in RC frames. But many other damage indices are presented and discussed in [7], for instance. It is a problem to evaluate to what extent the use of *P & A* index is proper for structures in NPP's.

Let D_ℓ ($\ell = \overline{1,L}$) denote the *local* damage intensity (index) at location ℓ or of component ℓ among the L possible locations / components under observation. Then a *global* damage intensity index can be naturally defined as the weighted average of D_ℓ's :

$$D_{\mathrm{T}} = \sum_{\ell=1}^{L} \omega_\ell D_\ell \quad \text{with} \quad \omega_\ell \in [0,1] \ \ \& \ \ \sum_{\ell=1}^{L} \omega_\ell = 1 . \tag{6}$$

In [4], these weights are associated to the *P & A* index

$$D = \frac{\theta_m}{\theta_u} + \frac{\beta}{M_y \theta_u} \int dE \tag{7}$$

by $\omega_\ell = E_\ell / \sum_{\ell=1}^{L} E_\ell$ where $E_\ell =$ the energy dissipated at location ℓ.

The damage indices (including the $P \cup A$ index) are often defined as taking values in the interval $[0,1]$. For the five damage states model (earlier mentioned) this interval could be partitioned as $[0,1] = [0, 0.2) \cup [0.2, 0.4) \cup [0.4, 0.6) \cup [0.6, 0.8) \cup [0.8, 1]$. If a weighted average as in Eq.(6) is applied on local damage indices $D_\ell \in [0,1]$ it clearly follows from this equation that $D_{\mathrm{T}} \in [0,1]$, too. There are other studies (like in the Spanish code mentioned in [8]) where weights are applied to several classes of structural typology in order to assess their relative importance, but these weights W_i are not subjected to the second condition following Eq.(6), that is $W_i \in [0,1]$ but it is no more required for their sum to be $= 1$. Anyway, if applied on damage indices, such weights keep them in $[0,1] : D_i \in [0,1] \Rightarrow W_i D_i \in [0,1]$.

4 SEISMIC DAMAGE PROBABILITY MATRICES

Another stochastic measure over the damage state set is the probability that the structural member / structure enters a damage state d_j after an earthquake occurrence provided its pre-earthquake damage state was d_i :

$$P_{ij} = P(D_{\text{post}} = d_j \mid D_{\text{pre}} = d_i) . \tag{8}$$

In [6], d_i, d_j are called damage levels, but they may be clearly called damage states. In fact, the probabilities in Eq.(8) are conditional probabilities, but with a different meaning than the ones in Eq.(4). These probabilities can be considered as the entries in a stochastic

stochastic transition matrix denoted (as in [6]) by CDTP (*c*onditional *d*amage *t*ransition *p*robability matrix). Hence

$$\mathrm{CDTP} = [P_{ij}]_{m+1,m+1} \tag{9}$$

with P_{ij} of Eq.(8). It is natural to combine Eqs. (6) & (8) resulting in twice-conditional probabilities, that is probabilities of damage state transitions conditional on a certain earthquake intensity level :

$$P_{ijk} = P(D_{\mathrm{post}} = d_j \mid D_{\mathrm{pre}} = d_i \ \& \ Y = y_k). \tag{10}$$

In Eqs. (6) & (8) it is natural to assume that $d_j \geq d_i$. This implies that $P_{ij} = P(D_{\mathrm{post}} = d_j \mid D_{\mathrm{pre}} = d_i) = 0$ if $j < i$; consequently, the CDTP matrix is upper-triangular. As regards the conditional probabilities in Eq.(10), they would lead to a 3-dimensional matrix

$$\mathrm{CEDTP} = [P_{ijk}]_{m+1,m+1,n} \tag{11}$$

i.e., a *c*onditional *e*arthquake (-induced) *d*amage *t*ransition *p*robability matrix. These models could be turned into time-dependent ones if the probabilities in Eqs. (8) & (10) are considered as being time-dependent :

$$P_{ij} = P_{ij}(t) \ \& \ P_{ijk} = P_{ijk}(t), \ t \in (0, T]. \tag{12}$$

Certainly, this dependence of time should be specifically modeled for the transition probabilities. Thus, the conditioning event in Eq.(8) would have a larger probability for increasing t due to the aging process of the structure or structural member. As regards the earthquake occurrence events, they clearly depend on the earthquake hazard model accepted. The probabilities in Eqs.(12) should be respectively defined as

$$P_{ij}(t, t + \Delta t) = P\big(D(t + \Delta t) = d_j \mid D(t) = d_i\big), \tag{13}$$

$$\begin{aligned} &P_{ijk}(t, t + \Delta t) = \\ &= P\big(D(t + \Delta t) = d_j \mid D(t) = d_i \ \& \ \mathbf{1}_{E_k}(\tau) = 1, \ \tau \in [t, t + \Delta t]\big). \end{aligned} \tag{14}$$

The probability in Eq.(14) should be read as follows : $P_{ijk}(t, t + \Delta t) =$ the probability that the component / structure enters the damage state d_j at moment $t + \Delta t$ provided it has been in state d_i at $t \in (0,T)$ and an eartquake of intensity (class) Y_k $(1 \leq k \leq n)$ has occurred at some moment $\tau \in (t, t + \Delta t)$. In Eq.(14), $\mathbf{1}_E(t) =$ the time-dependent indicator function of event E. Certainly, the conditional probabilities in Eqs. (6), (8), (10), (13), (14) could be reformulated by means of a damage intensity index (as in Eqs. (4) & (5)), but not this is the essential point.

A (3-dimensional) CEDTP matrix as in Eq.(11) can be turned into a (2-dimensional) *s*eismic *r*isk *t*ransition *p*robability matrix - abbreviated SRTP - if it is postmultiplied by a (column) vector of earthquake occurence probabilities. Let us recall that a vector of earthquake intensities $\mathbf{Y} = [y_1 \ldots y_k \ldots y_n]^{\mathrm{T}}$ was earlier considered in Section 2, and the probabilities associated with it can be written as $P(\mathbf{Y}) = [P(y_1) \ldots P(y_k) \ldots P(y_n)]^{\mathrm{T}}$,

$$\text{SRTP} = [Q_{ij}]_{m+1,m+1} = \text{CEDTP} \cdot P(\text{Y}) = \left[\sum_{k=1}^{n} P_{ijk} P(y_k) \right]_{m+1,m+1} . \quad (15)$$

As earlier mentioned (see Eq.(14)), the time-dependent risk analysis makes necessary to the entries in such a SRTP matrix to depend on time. The seimic vulnerability indices of [9] seem to be more appropiate for such an approach. A (seismic) vulnerability function is defined by

$$F_D(d,T) = \int_0^T \int_0^d \int_0^{y_{max}} f(\delta \mid y) f_Y(y,\tau)\, dy\, d\delta\, d\tau \quad (16)$$

where $f(d \mid y)$ is the conditional damage density function over the Y earthquake intensity and $f_Y(y,t)$ is the time-dependent intensity density function. $F_D(d,T)$ in Eq.(16) is the damage cumulative distribution function over the lifetime / operational cycle $[0,T]$ of the component or structure. It becomes a time-dependent damage *cdf* if T is replaced by $t \in [0,T]$ as the upper limit of the first integral in Eq.(16). The model given by Eq.(16) is applicable when the variables there involved can be considered as being random, independent and continuous on their defintion domains. Certainly, specific distributional assumptions must be assumed for these variables.

5 DAMAGE RISK MEASURES AND MAINTENANCE / REPAIR STRATEGIES

The most part of the analytic and stochastic models earlier presented (in Section 2-4) are not specific for degrading structures in nuclear power plants. They were developed especially for RC or steel components and (sub)structures in general facilities. However, the large amount of concrete / steel structures in NPP's gives a reason for considering such models, in particular from the point of view of inspection / maintenance and repair strategies. We are going to see how such damage risk models can be used for devising rational I / M / R strategies. Some paths to follow are suggested by references like [1,2,3,7].

If $[0,T]$ is the estimated service life interval, let $\{T_1, T_2, \ldots, T_K\}$ be the moments at which the inspections are planned to be performed. It follows that the operational cycle is partitioned by

$$(0,T] = \bigcup_{k=1}^{K} (T_{k-1}, T_k] \quad (17)$$

and let $T_k - T_{k-1} =_{\text{not}} \theta_k$. The intervals between two successive (routine) inspections could be taken as equal over the whole service life, that is $\theta_k = T/K \ (k = 1,2,\ldots,K)$, but we consider as more realistic to take shorter intervals between two inspections the older is the structure. Therefore we suggest to be applied some correction factors on T/K, i.e. $\alpha_k : \ \alpha_1 + \alpha_2 + \ldots + \alpha_K = K$ so that

$$\theta_k = \alpha_k \frac{T}{K} \ (k = 1,2,\ldots,K), \text{ with } \sum_{k=1}^{K} \theta_k = \sum_{k=1}^{K} \alpha_k \frac{T}{K} = \frac{T}{K} \sum_{k=1}^{K} \alpha_k = T. \quad (18)$$

These factors have to take values around 1, with values > 1 for smaller k's and < 1 for larger k's. A possible dependence on age of these factors is represented in Fig.2 below.

Another problem consists in choosing an adequate inspection-and-repair strategy for a *whole structure* consisting of several components. With reference to the assumptions (a) thru (d) of [1], let us denote by (e) the splitting (17) of the life time interval $[0,T]$ with the age-dependent intervals (18) between the successive inspections, and let us also admit another assumption on components in the structure : (f) The structure S under analysis is assumed to consist of a set C of components partitioned into J component classes (with $\mathrm{card}\, C = N$) such that

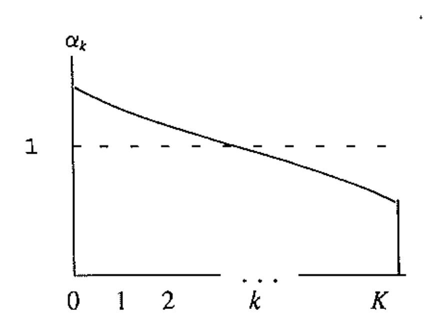

Fig.2 Age-dependent α_k's

$$C = \bigcup_{j=1}^{J} C_j \quad \text{or} \quad S = \bigsqcup_{j=1}^{J} C_j , \tag{19}$$

where C_j $(j = 1,2,\ldots,J)$ are classes of nominally identical (or highly similar) components operating in (very) similar conditions ; certainly, $j \neq \ell \Rightarrow C_j \cap C_\ell = \varnothing$. The special sign $\sqcup$ is used in the second expression of (19) for suggesting that the structure S is not merely a set union but a structured system consisting of components falling in specific classes of similarity. As as simplified example, let us mention a framed structure consisting of columns and beams.

In a similar way as in [1,2], we quantify the damage intensity $I_j(t)$, for any component in a similarity class C_j $(j = 1,2,\ldots,J)$, in terms of *damage intensity* indicators $X_j(t)$, but not for a certain location in a component; instead, for a component of class j. The remaining strength at time t is defined, for a component $c \in C_j$, as

$$R_c(t) = r_j^0 \cdot G_j(t) , \tag{20}$$

where r_j^0 is the initial (nominal) strength of any $c \in C_j$, (at $t = 0$), and $G_j(t)$ is the degradation function for any component in class C_j. Eq.(2) in assumption (d) of [2] becomes

$$G_j(t) = 1 - \max_{c \in C_j} \{ X_j(t) \} . \tag{21}$$

Another issue concerns the duration of in/off-service inspections and maintenace/repair operations. The time length of an inspection may be assumed as negligibly small with respect to the service life T (reaching 60 years, for instance). Instead, the durations of complex maintenance and repair operations cannot be accepted as negligible. Such a repair time interval occurs in Fig.1, where the shadowed vertical strip breaks the graph of the degrading function $\bar{g}(t)$. As regards the time lengths for the maintenance/repair operations of components, we propose another law to be applied instead of the one in Eq.(18) for the intervals between inspections : if a component $c \in C_j$ has entered a damage state $D_c(t) = d_j$ at moment t such that $d_j \geq \delta_r$ = the damage level at which a repair is necessary, then the repair time τ_c should be proportional to $d_j - \delta_{jr}$.

A more complete time-dependent model for degrading structures (in NPP's) should operate - in our opinion - with an extended set of states : the possible damage states considered in Section 3 have to be completed with states corresponding to : (i) operating state for the component / equipment (equivalent to $D_j(t) = d_0$ = no damage in the component $c \in C_j$), (*ii*) damage states $D_j(t) \in \{d_1, d_2, \ldots, d_m\}$, (*iii*) off-service inspection states, (*iv*) maintenace / repair states.

It is thus rational to consider a set of states Σ and a random function of time σ, that is $\Sigma = \{s_0, s_1, s_2, \ldots, s_m, s_{m+1}, s_{m+2}\}$, $\sigma : [0, T] \longrightarrow \Sigma$ such that for $(\forall\ t \in [0, T])$ $P(\sigma(t) = s_i \in \Sigma) = p_i(t)$. In fact, this probability should be defined as a conditional one by the state of the component / structure at some earlier moment : $(\forall\ t \in [0, T])$ $p_{ij}(t, \Delta t) = P(\sigma(t + \Delta t) = s_j \mid \sigma(t) = s_i)$. Let os only mention that the entries in such transition matrices would be defined as in Eq.(13) but with D, d_i, d_j respectively replaced by σ, s_i, s_j $(0 \le i, j \le m+2)$. Taking into account the decomposition of the system in Eqs.(19), a CSTP matrix (as in Eq.(13)) should be derived for each component class $\ell \in \{1, 2, \ldots, J\}$ using class-specific functions σ_ℓ. An overall (or global) transition matrix for the system should be assembled from the component CSTP matrices $\mathrm{CSTP}_\ell(\Delta t)$ $(\ell \in \{1, 2, \ldots, J\})$ using a weighted average formula (similar to Eq.(6)) :

$$\mathrm{OSTP}(t, \Delta t) = \omega^{\mathrm{T}}\left([P(\sigma(t))]^{\mathrm{T}}\mathrm{CSTP}(\Delta t)\right) = \omega^{\mathrm{T}} P(\sigma(t + \Delta t)) . \qquad (22)$$

where $\sigma(t) \in \Sigma^J$ is the state vector at time t.

6 CONCLUDING REMARKS

Time-dependent models for degrading structures have been discussed. The Markov models caould be taken into account, but it must be seen whether they are well suited to represent the time evolution of components in NPP's over the set of states just proposed. We do not extend this discussion here since problems of this type are approached in another paper submitted to this conference. Let us only mention that Eq.(22) could be used for selecting appropriate maintenance strategies for a component and system.

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