STRUCTURAL MECHANICS IN REACTOR TECHNOLOGY

Transactions of the 14th International Conference on
Structural Mechanics in Reactor Technology
Lyon, France, August 17-22, 1997

VOLUME 10

Division M

Reliability of Mechanical Components and · Structures

Coordinators : B. Ellingwood, G. Schueller

French Correspondent : E. Ardillon

Division P

Mechanical Consequences of Severe Accidents

Coordinators : B. Bolshov, I. Catton, G. Van Goethem

French Correspondent : J.C. Bouchter

Reliability-based condition assessment and service life prediction of steel containments and liners

Bruce R. Ellingwood* and Baidurya Bhattacharya[†]

* Professor and Chairman, Department of Civil Engineering, The Johns Hopkins University, Baltimore, MD, USA

† Postdoctoral Fellow, Department of Civil Engineering, The Johns Hopkins University, Baltimore, MD, USA

ABSTRACT: Steel containments and liners in nuclear power plants (NPPs) may be exposed to aggressive environmental effects over their service lives. The reliability of a typical NPP steel containment exposed to general corrosion and cumulative thermal creep damage, and subject to internal pressurization is investigated in this paper. Randomness in load and strength variables, in corrosion loss and in creep damage growth rate are considered.

1. INTRODUCTION

Steel containments and liners in nuclear power plants (NPPs) may be exposed to aggressive environmental effects that may cause their strength and stiffness to decrease over their service lives. During the past decade, there have been 32 reported cases of containment pressure boundary degradation in the 109 commercial NPPs licensed to operate in the U.S. (Naus et al, 1996). Corrosion has been detected in the steel containments and liners of 18 NPPs, where local thickness loss of up to 50% has been reported in a few instances. Other effects having the potential to cause structural deterioration are fatigue, including crack initiation and propagation to fracture, and elevated temperature creep and irradiation effects. Although the physics of these damage mechanisms are reasonably well understood and quantitative evaluation of their effects on time-dependent structural behavior is possible in some instances, such evaluations are difficult and remain novel. The assessment of existing steel containments and liners in NPPs for continued service must provide quantitative evidence that they are able to withstand future extreme loads during a service period with an acceptable level of reliability. Rational methodologies to perform the assessment can be developed from mechanistic models of structural deterioration, using time-dependent structural reliability analysis to take loading and strength uncertainties into account. Research is in progress to develop such methodologies, which include: (i) mathematical models to evaluate structural degradation, (ii) methods to assess the probability that containment or liner capacity has not degraded or will not degrade during a future service period, and (ii) statistically-based sampling plans for nondestructive evaluation.

2. STRUCTURAL AGING

2.1 Damage-causing mechanisms

Corrosion is perhaps the most significant damage mechanism affecting steel containments and liners. Uniform corrosion causes a thinning of section, leading to gross inelastic deformations or instability of the metal shell. Pitting corrosion is a localized effect, leading to leakage or loss of pressure boundary. The penetration, $Z(t)$, of uniform or pitting corrosion can be modeled by,

$$Z(t) = C(t - T_I)^M ; \quad t > T_I \tag{1}$$

in which C = rate parameter, which generally should be modeled as a stochastic process, M = time-order parameter, typically about 2/3 for carbon steel, and T_I = random initiation period. Statistics of parameters C and T_I must be determined from experimental data, and depend on the mechanism (e.g., uniform or pitting corrosion) and the environment. If $C(t)$ is modeled as a stochastic process, its correlation structure also must be characterized. Since it is not known *a priori* what kind of corrosive environment may exist at the critical location of a particular NPP containment, different sets of statistics for these random variables (based on available data compiled and analysed by Ellingwood et al, 1996) have been adopted later in this paper.

In contrast to corrosion, some damage mechanisms, such as fatigue, ductile deformation and elevated-temperature creep involve microstructural changes in the steel that either may not become detectable by common nondestructive evaluation methods until damage has already occurred or may become evident only at the point at which damage is accelerating rapidly. Continuum damage mechanics (CDM) deals with the characterization and analysis of growth of strength-reducing microstructural defects with the help of macroscopic state variables (Lemaitre, 1984). CDM makes it feasible, using the isotropic damage variable, D ($0 \leq D \leq 1$), to predict the effects of damage processes on structural components and systems and to estimate their residual strength or service life prior to the development of detectable flaws. Expressions for damage can be developed from principles of thermodynamics, and have been validated with limited experimental data (e.g., Bhattacharya and Ellingwood, 1996).

2.2 Description of structure

A steel containment can be idealized as a cylindrical shell of radius r and thickness h_0 with a hemispherical top also of radius r and thickness h_0. It has ring stiffeners of cross-sectional area A_1 placed circumferentially at intervals of s_1. Vertical stringers of area A_2 are placed at intervals s_2 circumferentially on the cylindrical portion of the shell. The shell has penetrations at different positions for access. A detailed finite element analysis is required to accurately analyze a shell with stiffeners and discontinuities (e.g., Cherry, 1996). However, as pointed out by Greimann et al (1982), a limit analysis provides a reasonable and conservative approximation of general shell behavior, and is deemed sufficient for the purposes of the present analysis. The shell is fabricated of SA 516 grade 70 steel which has a specified yield strength of 262 MPa and tensile strength of 483 MPa.

3. LOAD MODELING

Loss of coolant accidents are accompanied by a rise in temperature and pressure within the containment (Hwang et al, 1987). Such accidents are extremely rare events — the estimated rate of occurrence being of the order of 10^{-3}/yr to 10^{-4}/yr (Hwang et al,

1987) — and therefore, for the purpose of the present analysis, the occurrence such events can be modeled as a *point process* in time when compared to the scale of the service life of interest, which is typically 40 to 60 years. The underlying physical process of events leading to a pressure build-up can be broadly grouped into (i) pure "chance" phenomena, like human error, the frequency of which remains essentially constant in time, and (ii) "aging" phenomena that might cause safety systems to malfunction, the propensity of which may increase with time in the absence of corrective intervention. Let the mean rate of occurrence of the "chance" process be λ_0, and let the mean rate of occurrence of the "aging" process be denoted by an increasing function $\lambda_A(t)$. Previous studies of time-dependent reliability of steel containments have not considered the latter aspect of load occurrence. The purpose of including this in the present analysis is to see if an increasing rate of occurrence of design-basis events has a significant impact on the reliability of this and similar structures.

Let us now make some assumptions about the point processes, $N_0(t)$ and $N_A(t)$, that describe the number of occurrences of events arising from chance and aging, respectively. Once there is an accidental event during the service life, any mitigating equipment is assumed to be repaired or replaced, so that the cause of the present event has no bearing on future events. Also, since the aging and chance processes have different origins, it is reasonable to assume that $N_0(t)$ and $N_A(t)$ are statistically independent at all t. Then $N_A(t)$ and $N_0(t)$ can be assumed to be independent *Poisson processes*, and their sum, $N(t) = N_A(t) + N_0(t)$, which represents the overall occurrence of accidental pressures, is also a *Poisson process* with mean rate of occurrence

$$\lambda(t) = \lambda_0 + \lambda_A(t). \qquad (2)$$

In the presence of aging, the occurrence of internal pressure and temperature is a non-homogeneous Poisson process. The rate function of $N_A(t)$ can be written as

$$\lambda_A(t) = \frac{\alpha}{u} \left(\frac{t}{u}\right)^{\alpha-1} \qquad (3)$$

in which u, α are parameters, consistent with the common assumption that failure times are described by a Weibull distribution. For $\alpha > 1$, the rate of occurrence increases with time and represents a realistic "aging" process.

4. RELIABILITY OF AGING CONTAINMENT

The failure probability of the component can be evaluated as a function of time (or for some interval of time) if stochastic processes that define the damage mechanism, residual strength, and service loads are known or can be determined. We illustrate this for two damage mechanisms: general corrosion and elevated temperature creep.

4.1 Design considerations

The design equation for the ring-stiffened cylindrical shell is (Ellingwood et al, 1996):

$$S_{mc} = \frac{F_{yn}}{S_F} \geq D_n + L_n + P_n \qquad (4)$$

where F_{yn} is the nominal yield stress, $S_F = 1.97$ is the nominal safety factor at first yield (ASME, 1986), and D_n, L_n and P_n are the stresses caused by the nominal dead, live and accidental pressure loads respectively. The subscript n is used to emphasize the nominal values of the variables, which are usually different from their respective

Variable	Nominal(design) value	Statistical properties
Radius r	55 ft (16.8 m)	deterministic
Original thickness, h_0	1.375 in (34.9 mm)	deterministic
Stringer area, A_1	24.0 in^2 (155 cm^2)	deterministic
Stringer spacing, s_1	10 ft (3 m)	deterministic
Peak accidental pressure, P_a	40 psig (0.28MPag)	Type I max ($0.8P_{des}$,20%)
Peak accidental temperature, θ_a	390°F (199°C)	Type I max (177°C,20%)
Significant duration, Δt	20 min	Lognormal (1000s,30%)
Yield stress, F_y	38 ksi (262 MPa)	Lognormal ($1.10F_{yn}$,7%)

Table 1: Original (uncorroded) dimensions, load and strength statistics (the statistical parameters enclosed in parentheses are mean and c.o.v.)

mean values (Table 1, based on Hwang et al, 1987). In view of the stringent quality control during the construction of NPP's, the dimensional variabilities are considered insignificant and are treated as deterministic.

In an elastic analysis, the circumferential stress in the shell membrane caused by pressurization inside the shell is

$$P_n = P_{des}\frac{r}{h_0} \tag{5}$$

where P_{des} is the nominal value of the peak pressure used in the design, and r and h_0 are radius and initial thickness of the shell, respectively. Assuming that the dead and live loads are negligible when the shell is subjected to internal pressure, the design thickness of the shell is (Eqs 4 and 5):

$$h_0 = S_F\frac{P_{des}}{F_{yn}}r = \frac{P_{des}}{S_{mc}}r \tag{6}$$

Using the nominal values listed in Table 1, $h_0 = 35mm$.

4.2 Limit state under internal pressurization

As the shell begins to deform in the event of a pressure build-up, the attachments to the containment fail prior to general shell failure, thanks to the large ductility of carbon steel. Finite element modeling (Greimann et al, 1982; Cherry, 1996) suggests that the governing limit state of the shell is that of excessive general inelastic deformation. The pressure corresponding to the onset of the critical deformation (or equivalently, the critical strain) is termed the *limit pressure*, p_0, which, for an axi-symmetric ring-stiffened shell, is

$$p_0 = F_y\frac{H(t)}{r}\gamma \tag{7}$$

where F_y is the random yield stress, $H(t) = h_0 - Z(t)$ is the random thickness of the shell at time t, and γ takes into account the plastic deformation of the shell at failure (taken equal to the amount of elastic deformation at yield) and the effects of the stiffeners (Greimann et al, 1982):

$$\gamma = \frac{2}{\sqrt{3}} + \alpha_1 \quad ; \quad \alpha_1 = \frac{A_1}{s_1 H(t)} \tag{8}$$

The limit state, $p_0 - P_a = 0$, in which P_a is the random peak accidental pressure, can now be written as:

$$\gamma(t)S_F X\frac{H(t)}{h_0} - Y(t) = 0 \tag{9}$$

4

where the normalized quantities are $X = F_y/F_{yn}$ and $Y = P_a/P_{des}$.

The degradation processes due to corrosion are assumed to occur slowly enough that the time-dependent resistance variables $(\gamma(t),\ H(t)/h_0)$ can be treated as constants during the duration of an accidental pressurization (Ellingwood and Mori, 1993). For brevity, let $R(t)$ denote the random process representing the resistance (eq 9)

$$R(t) = \gamma(t)S_F X \frac{H(t)}{h_0} \tag{10}$$

and let $r(t)$ denote one realization of the random process. The reliability of the shell at time t, given n occurrences of accidental pressurization at known times $t_1^*, ..., t_n^*$ (in increasing order), can then be expressed as

$$\mathrm{P}[T_f > t | N(t) = n, \underline{T}^* = \underline{t}^*] = \mathrm{P}[\cap_{i=1}^n R(t_i^*) > Y(t_i^*)] \tag{11}$$

where T_f is the random time to failure. Assuming that the peak pressures occurring at different times are statistically independent, and the peak pressures are identically distributed, the conditional reliability simplifies to

$$L(t|A) = \mathrm{P}[T_f > t|A] = \prod_{i=1}^n F_Y[r(t_i^*)|A] \tag{12}$$

where the common probability distribution of the peak pressures is $F_Y(\cdot)$ and the event $\{A\} = \{N(t) = n, \underline{T}^* = \underline{t}^*, X = x, C = c, M = m, T_I = t_I\}$ We now remove the conditioning event $\{A\}$ and obtain the reliability at time t (assuming statistical independence between each pair of X, C, M, T_I and using the theorem of total probability) as (Bhattacharya, 1997):

$$L(t) = \int_x \int_c \int_m \int_{t_I} \exp\left[-\Lambda(t)\left(1 - \int_0^t F_Y[r(s)|A]\ \frac{\lambda(s)ds}{\int_0^t \lambda(v)dv}\right)\right] \times$$

$$f_X(x)f_C(c)f_M(m)f_{T_I}(t_I)dx\ dc\ dm\ dt_I \tag{13}$$

Example: Figures 1 (a) and (b) show the effects of corrosion rate, equipment aging and chance occurrence rate on the cumulative failure probability (CFP), $F_{T_f}(t) = 1 - L(t)$, of the ring-stiffened shell. The corrosion parameters, $M \sim$ Normal (0.7, 20%) and $T_I \sim$ Lognormal (10yr, 30%) in all cases, and C is lognormal with c.o.v. of 30% and mean of $600\mu m/yr^M$ (for "severe" corrosion, where mean of $Z(60) = 0.27h_0$) and $300\mu m/yr^M$ (for "moderate" corrosion, where mean of $Z(60) = 0.10h_0$). The aging parameters (eq 3) are $\alpha = 2$ and $\mu = 120yr$.

The reliability of the containment is found to depend significantly on the corrosion rate. Ignoring "severe" corrosion can cause more than 4 orders of magnitude under-prediction in the CFP. Neglecting the effect of aging on $\lambda(t)$ in the presence of a comparatively low λ_0 also may lead to a considerable under-prediction of the CFP. This observation suggests that frequently testing certain items of equipment, which may cause the equipment to age, may have a less than beneficial impact on risk.

4.3 Thermal creep damage accumulation

During the course of a design-basis event (based on the data available in Hwang et al, 1987), the temperature and pressure within the containment rise in a very short time ($\sim$ 10 sec) to their peak values, P_a and θ_a respectively, and remain steady at the
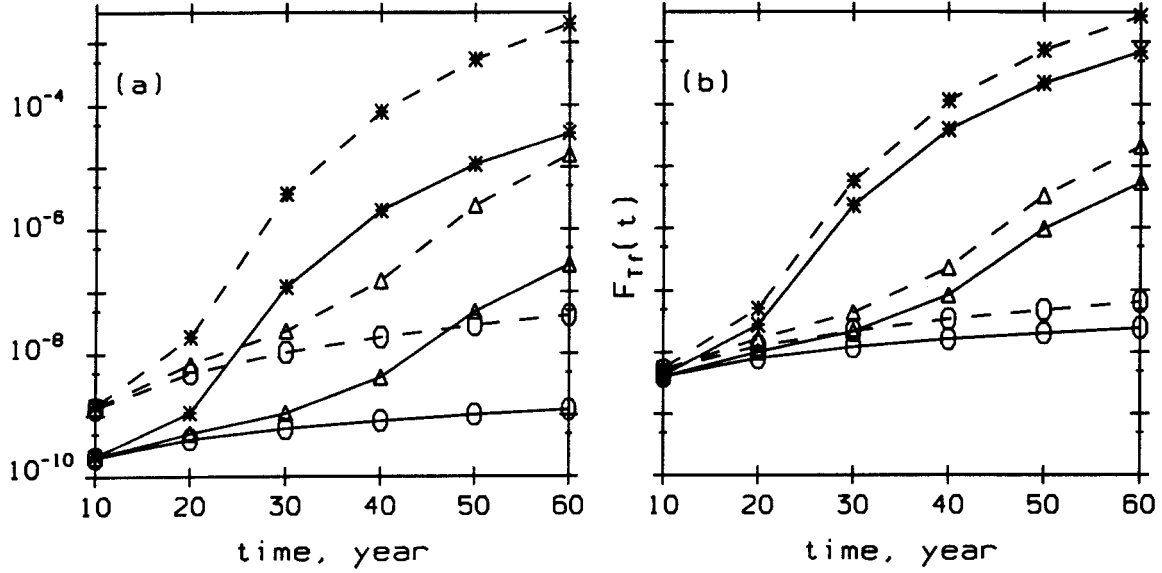
Figure 1: CFP under different rates of corrosion (∗ severe, $\triangle$ moderate, 0 zero) and aging (——— $\mu = 120yr$, — — — no aging), (a) $\lambda_0 = 0.0001/yr$ (b) $\lambda_0 = 0.002/yr$

peak values for a duration of Δt (~ 20 min). The pressure drops off relatively quickly and attains the base value in less than one day. The temperature however takes longer to return to its base value ($\sim 120°F$). The peak pressure and temperatures in events occurring at different times are assumed to be statistically independent and identically distributed. However, P_a and θ_a may be statistically dependent during a design-basis event. In the event of a pressure and temperature build-up, creep damage may occur during a time-interval Δt, at the constant (constant in any given realization of the process) temperature θ_a under the action of the constant load P_a. The action of the load appears in the form of the membrane stress, which is aggravated by corrosion loss. Steady state creep strain rate can be described by the Norton-Bailey law,

$$\dot{\epsilon}_{cr} = A(\tilde{\sigma})^m \tag{14}$$

where A, m are empirical temperature-dependent parameters, and $\tilde{\sigma}$ is the effective stress, defined in terms of the isotropic damage variable, D, as $\tilde{\sigma} = \sigma/(1 - D)$, σ being the nominal stress.

Suppose that n loads occur during the life (t_L) of the structure at random instants of time, t_i ($i = 1, 2, \ldots, n$). The damage, $D(\Delta t_i)$, accumulated at the end of the ith load occurrence may be expressed through a stochastic differential equation as (Bhattacharya, 1997):

$$(1 - D(\Delta t_i))^{m_i+1} = (1 - D(\Delta t_{i-1}))^{m_i+1} - A_{1i}(m_i + 1)\Delta t_i - B_{1i}(m_i + 1)W(\Delta t_i) \tag{15}$$

where $W(\Delta t_i)$ is the increment in a standard Wiener process that describes random fluctuations in the thermodynamic state variables during the interval Δt_i. The time and temperature dependent coefficients, during the ith occurrence, are:

$$A_{1i} = \frac{4}{3}\frac{A_i}{\sigma_{f_i}}\sigma_{\infty i}^{m_i+1}, \qquad B_{1i} = \frac{4}{3}\frac{A_i}{\sigma_{f_i}}\sigma_{\infty i}^{m_i}(\sqrt{c_4}/c_3)_i \tag{16}$$

where σ_f is the true failure stress, and $(\sqrt{c_4}/c_3)$ is the noise intensity describing inherent randomness in the creep damage accumulation law. The subscript $_i$ denotes their values

at temperature θ_{a_i}. The far-field stress, σ_{∞_i} depends on the shell radius, r, the pressure P_{a_i} and the shell thickness, H_i at time t_i (cf eq 5). Eq (15) can be solved recursively, which allows the accumulated creep damage after n loads, D_n, to be written in terms of the initial damage, D_0 (Bhattacharya, 1997). Due to the nature of creep damage accumulation, D_n is an increasing function of n.

Failure, defined as the formation of a macro-crack (localization of damage), occurs when the accumulated damage exceeds the critical damage, $D_c \leq 1$, which is a material property. The conditional cumulative failure probability is

$$F_{T_f}(t_L|N(t_L) = n) = \mathrm{P}[D_n \geq D_c] \tag{17}$$

where the statistical independence of the Wiener increments at events i and j $(i \neq j)$ may be used. The conditioning can be removed by the theorem of total probability

$$F_{T_f}(t_L) = \sum_{n=0}^{\infty} F_{T_f}(t_L|N(t_L) = n)P(N(t_L) = n) \tag{18}$$

With the load occurrences being sufficiently rare events, only a few terms need to be considered in this summation (18).

Example: A schematic representation of creep damage accumulation in an aging and corroding steel containment is shown by the sample function in Figure 2 (a). A design-basis event occurs at each discontinuity of the sample path (the rate of occurrence of events has been greatly magnified in this figure to illustrate the concept). The instantaneous jumps underline the fact that the duration of the elevated temperature is very small compared to the scale of reliability computations. The acceleration in damage growth later in the life of the structure is partly due to the increasing corrosion loss which amplifies the shell membrane stress.

Figure 2 (b) shows the CFP due to creep damage accumulation in the steel containment as a function of time in the presence of "moderate" corrosion. The creep parameters, $A(\theta)$ and $m = 4.7$ are from Harmathy (1967), and P_a, θ_a and Δt are from Table 1. The noise parameter is assumed to be $\sqrt{c_4/c_3} = 138MPa\sqrt{hr}$, and the true failure stress has been assumed constant at $552MPa$. A correlation coefficient of 0.60 between θ_a and P_a has been assumed. The initial damage, $D_0 = 0$ (deterministic), and the critical damage is assumed to be normally distributed with mean 0.5 and COV 20%. The conditional failure probabilities increase with the number of events; however the probabilities of 2 or more occurrences rapidly decrease, and not more than three terms need to be considered in the expansion (eq 18) (Bhattacharya, 1997). The CFP due to creep damage accumulation (Fig 2 (b)) is found to be orders of magnitude lower than that due to the deformation limit state associated with internal pressurization (Figs. 1) under similar conditions. Thus, elevated temperature creep of the shell apparently is unimportant as a limit state.

4. CONCLUSION

Time-dependent reliability analyses have been performed for structures subjected to the damage mechanisms identified above. Uniform corrosion appears to have the most significant impact on reliability of steel containments and liners. In contrast, creep damage is inconsequential. Stochastic CDM is shown to provide a means for assessing margins of safety for structures when damage is not visibly manifested.
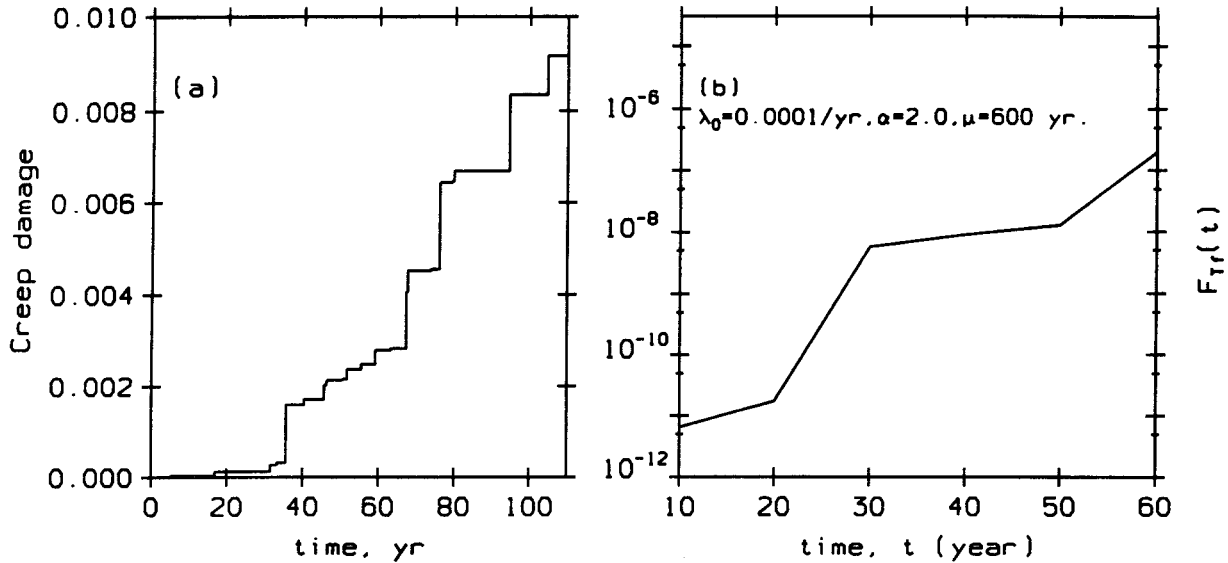
7

Figure 2: (a) Sample path, and (b) CFP due to creep damage

REFERENCES

ASME (1986). *ASME Boiler and Pressure Vessel Code, Section III, Division I*, American Society of Mech. Engrs.

Bhattacharya, B. (1997). *A Damage Mechanics Based Approach to Structural Deterioration and Reliability*, PhD thesis, Johns Hopkins University, Baltimore, MD, USA.

Bhattacharya, B. and Ellingwood, B. (1996). "A damage mechanics- based approach to structural deterioration." Proc. 11th Engrg. Mech. Specialty Conf., ASCE, New York, NY:588-591.

Cherry, J. L. (1996). "Analyses of Containment Structures with Corrosion Damage", *Proc. Water Reactor Safety Information Meeting*, Rockville, MD, October, 1996.

Ellingwood, B.R. and Mori, Y. (1993). "Probabilistic methods for condition assessment and life prediction of concrete structures in nuclear power plants", *Nuclear Engineering and Design*, 142:155-166.

Ellingwood, B., et al (1996). "Reliability-based condition assessment of steel containments and liners." NUREG/CR-5442, US Nuclear Regulatory Commission, Washington, DC.

Greimann, L. G. et al (1982). *Reliability Analysis of Steel Containment Strength*, Report NUREG/CR-2442, June 1982.

Harmathy, T. Z. (1967). "A comprehensive creep model", *Journal of Basic Engineering, Trans ASME*,89:496-502.

Hwang, H., et al (1987). " Probability-based design criteria for Nuclear Plant Structures", *J. of Str. Engrg.*, ASCE, 113(5):925-942.

Lemaitre, J. (1984). "How to use damage mechanics." *Nuc. Engrg. & Des.*. 80:233-245

Naus, D. J., et al (1996). "Aging of the containment pressure boundary in light water reactor plants", *Proc. Water Reactor Safety Information Meeting*, Rockville, MD, October, 1996.