Structural reliability of prestressed concrete nuclear containment under combined loads

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1 INTRODUCTION

Reliability analyses offer the possibility of structural risk asessment in terms of probability providing more information in decision-making than the simple yes or no answer resulting from deterministic approaches. Best estimates of structural reliability are necessary for NPP containments in order to accurately evaluate the probability of accidental radioactive release.

The paper presents the main methodological aspects and the numerical results of a structural reliability analysis carried out for a prestressed concrete containment subjected to multiple loads. The case study refers to a typical cylindrical shell with a hemisperical upper dome and a rigid basemat. All the load effects are treated as random quantities. The macroscale time variation of earthquakes and accidental overpressures are idealized assuming the Poisson arrival law.

The concrete crushing and cracking at the inside surface of the prestressed concrete containment are considered as limit state conditions related to the deterioration of the epoxy liner. A simplified estimation of the through-the-wall cracking limit state is included.

To carry out a reliable seismic analysis of the reactor building a proper modeling of the soil-structure interaction (SSI) effects must be made. It is to be noted that even for hard rocks having a high shearwave velocity of 1500 m/s the SSI effects influence the structural response by 10 - 15% (Ghiocel and Stefănescu 1986).

The overall structural reliability of the reactor containment was estimated taking into account the occurence rates of hazardous loads as well as the conditional limit state probabilities. Positive correlation between earthquake intensities and accidental overpressure occurences are included .

2 CONTAINMENT LOAD EFFECTS

The earthquake load was modeled as an intermittent continuous process. The earthquake occurences were idealized by Poisson pulse processes with different mean occurence rates and durations depending on the seismic motion intensity. To estimate the overall structural seismic risk the random variation of earthquake peak accelerations was descretized in increments of 0. 05 g in the range of 0. 05 - 0. 80 g. , corresponding to 10^{-1} - 10^{-7} occurence probabilities (seismic

hazard curves).

The earthquake ground acceleration time history at the soil surface was idealized as a nonstationary Gaussian stochastic process with mean zero and Kanai – Tajimi time - invariant spectral power density $S_{aa}(w)$:

$$(1) \qquad S_{aa}(w) = S_o \left[1 + 4\xi_g^2 (w/w_g)^2 \right] \Big/ \left\{ \left[1 - (w/w_g)^2 \right]^2 + 4\xi_g^2 (w/w_g)^2 \right\}$$

Where S_o represents the power spectral intensity of the earthquake and w_g and ξ_g denote the dominant ground circular frequency and the ground damping ratio, respectively. The w_g and ξ_g values depend on the local soil conditions of the given site. The values of the parameters w_g and ξ_g were differently chosen for the horizontal and vertical motion in order to describe the specific frequency content of the seismic signal in the two directions. The amplitude of the vertical acceleration corresponds to 2/3 of the horizontal amplitude.

For the investigated PHW type reactor the design values of the accidental internal pressure (P_1) is achieved when "a 100% break" of the pump suction piping of the Primary Heat Transfer System (PHTS) takes place resulting in the highest discharge rate into the containment.

In the case of small breaks in PHTS the internal pressure (P_2) is significantly lower around 60% of P_1. Such accidental overpressure P_2 may have a higher annual rate of occurence than the large LOCA pressure P_1.

If the suppression system (dousing system) fails or hydrogen deflagration due to core melt is produced the accidental overpressure can increase several times. However, such an event occurs with a probability lower than 10^{-7}(triple failure event). A mean overpressure of 3. 6 daN/cm^2 (P_3) was considered.

The quasistatic loads generated by the uniformly distributed internal accidental pressures were modeled as Poisson rectangular pulse processes having specified mean occurence rates and durations but random intensities. For accidental pressure P_1 the mean occurence rate λ_{P_1} and the mean duration μ_{P_1} are 10^{-4} ev/yr and 100 s, while for the pressure P_2 the same parameters λ_{P_2} and μ_{P_2} take the values 10^{-3} ev/yr and 600 s, respectively. Marginal distributions of accidental pressure intensities are of extreme type I, Gumbel. The means and the coefficients of variation are P_1 = 1. 20 daN/cm^2 and V_{P_1} = 20% and P_2 = 0. 75 daN/cm^2 and V_{P_2} = 20%, respectively.

The seismic induced accidental overpressures were also considered as possible events in the reliability analysis via Load Coincidence formulation (Pearce and Wen 1983). For such events the coincidence rate was evaluated assuming different conditional occurence probabilities depending on the earthquake intensities.

For dead (D) and live loads (L) it was conservatively admitted that the mean values are equal to the design values. The same assumption was also admitted for temperature (T) , concrete creep (C) and shrinkage (S) effects. The coefficients of variation are $V_D = V_L = 5\%$ and $V_T = V_C = V_S = 10\%$.

For forces due to cable prestressing (F) are all treated as individual load cases applied to each structural component of the containment. The mean values of prestressing forces are 10% higher than the design values. Coefficients of variation $V_F = 10\%$ were applied for each set of prestressing cables.

3 STRUCTURAL COMPUTATIONAL MODELS

Detailed finite element computational models were used in order to evaluate

the stress state in the reactor containment structure. Only the main aspects concerning the seismic analysis are given in this chapter.

The SSI analysis was performed using FLUSH computational code (Lysmer, Udaka, Tsai and Seed 1975). The assumption of vertical propagation of S and P seismic waves was accepted. The nonlinear and hysteretic behaviour of soil was modeled by Seed - Idriss equivalent linear procedure. Transmitting and viscous boundaries were used to simulate the semi-infinite nature of the surrounding soil deposit. Using the complex response method (Fourier transform procedure) the nonproportionality of damping matrix of the soil-structure system was included. A second computational step consisting in a seismic analysis of a more detailed structural model, excited with the time histories resulted from the previous step, was applied.

In the present investigation the soil shear stiffness G (γ) are stochastically idealized as independent normal random variable with coefficients of variation of 30%. The uncertanty related to the shape of the curve G (γ) / G_o - γ was not explicitely modeled; only G_o and D (γ) were considered as stochastic variables. It is to be noted that for the investigated containment the uncertainties in soil properties influence more significantly the structural response than the uncertainties in earthquake ground motion for a given peak acceleration level.

4 RELIABILITY ANALYSIS PROCEDURE

In order to calculate the structural reliability of the containment, a first-order approximate solution of the overall limite state (failure) probability P_f was used:

$$(2) \qquad P_f \simeq 1 - e^{-\sum_j \lambda_j T}$$

where λ_j is the overall mean crossing rate out of the safe domain in the critical section j and T is the reference time interval.

Using Load Coincidence formulation the λ_j values can be expressed as follows:

$$(3) \qquad \lambda_j = \sum_k \lambda_{kj} \cdot P_{jk} + \sum_k \sum_{l>k} \lambda_{jkl} \cdot P_{jkl}$$

in which P_{jk} is the conditional limit state probability in the critical section j given the occurence of a single hazardous load S_k (t). The values λ_{jkl} and P_{jkl} are the mean crossing rate and the conditional limit state probability in critical section j, given the coincidence of hazardous loads S_k (t) and S_l (t). The conditional probabilities P_{jk} and P_{jkl} were evaluated based on structural analyses. Seismic fragility curves were convolved by the occurence rate function of earthquake (seismic hazard curves).

Approximate solutions were obtained by Monte Carlo simulation via Response Surface technique (Mazumdar, Marshall and Chay 1978). The procedure is represented algebrically as follows:

$$(4) \qquad \bar{R}_{fem,\,RS}(p_1, p_2 \cdots p_n) \simeq R_{fem}(\bar{p}_1, \bar{p}_2 \cdots \bar{p}_n)$$

$$(5) \qquad \sigma_{R_{fem,RS}}(p_1, p_2 \cdots p_n) \simeq \sigma_{RS/\overline{RS}} \cdot R_{fem,RS}(\bar{p}_1, \bar{p}_2 \cdots \bar{p}_n)$$

where $\overline{R}_{fem,RS}$ and $\sigma_{R_{fem,RS}}$ are the mean and the standard deviation of the probabilistic response $R_{fem,RS}$ evaluated for finite element structural model via RS technique; $R_{fem}(\bar{p}1, \bar{p}2 \ldots \bar{p}n)$ is the deterministic response corresponding to the mean values $\bar{p}1, \bar{p}2 \ldots \bar{p}n)$ of the input random parameters $\bar{p}_1, \bar{p}_2 \ldots \bar{p}_n$; $\overline{RS}$ and σ_{RS} represent the mean and the standard deviation of the probabilistic response obtained by Monte Carlo trials using the RS function.

For predicting the biaxial concrete failure at the inside surface of the prestressed concrete containment to excessive tension, assuming that surface cracking depends only on the major and minor principal stress, a modified two- parameter model according to Mohr - Coulomb criterion was accepted.

A conservative simplified estimation of through-the-wall cracking limit state was obtained using higher equivalent values for concrete tensile strength.

5 LIMIT STATE PROBABILITIES AND CONCLUDING REMARKS

The structural reliability analysis refers to the evaluation of (i) conditional cracking probabilities at the inside surface of the prestressed concrete containment subjected to specific load combination and (ii) the overall probability at the inside surface of the containment and through-the-wall.

Conditional limit state probabilities were estimated for the following load combinations:

(6) $D + L + F + P_1 + T$

(7) $D + L + F + E_D + T$

(8) $D + L + F + E_D + P_2 + T$

(9) $D + L + F + E_D + P_1 + T$

where D, L, F and T are the structural effects induced by dead loads (D) live loads (D) live loads (L) including concrete creep and shrinkage , prestressing forces (F) and summer shutdowm temperatures (T). E_D denotes the extreme earthquake postulated in the NPP design, as DBE (Design Basis Earthquake) in the Canadian standards, or SSE (Safe Shutdown Earthquake) in U. S. regulations. P_1 and P_2 are the accidental internal pressures due to large and small LOCA, respectively.

In order to evaluate the structural reliability of the containment structure, first the critical sections specific to each load combination scenarios must be identified. The figure 1 presents the variation of the conditional cracking probabilities at the inside surface of the prestressed concrete containment subjected to different load combinations. Upperbounds of the conditional cracking probabilities and the related sections are given in tabel 1.

Two critical sections of primary interest in the reliability analysis are noted: (i) Perimeter wall, at about 8 m above the upper face of the basemat of the reactor building , in meridional direction (explained by the presence of hinge at the base of the perimeter wall) and (ii) Upper dome, near the ring beam, in meridional direction. The former section is critical to the load combinations including the extreme earthquake E_D (DBE or SSE), while the latter section is critical for load combinations including major accidental overpressure P_1.

Sensitivity studies have shown that the conditional limit state probabilities are greatly influenced by the variation in prestressing forces or concrete creep and shrinkage induced effects. If temperature variations other than those corresponding to summer shutdown are used lower cracking probabilities are obtained. For exemple, in the critical section of the upper dome the neglect of favourable effects of concret creep and shrinkage increases the conditional cracking probability from 3×10^{-5} to 5×10^{-3} for the load combination $D+L+F+P_1 + T$.

It can be noted from the tabel 1 that for the investigated containment structure the superposition of E_D and P_1 or P_2 is not essential. Their maximum values are not superimposed in the critical sections (figure 1). More important is the accurate assessment of concrete creep and shrinkage values. However, the situation may be different for other types of reactor containments.

Table 1. Upperbound conditional cracking probabilities

Load combination	Critical section[x]	Direction	Probability
$D+L+F+P_1+T$	UD-radius 20.5 m	Meridional	5.10^{-3}
	PW-height 8.0 m	Hoop	10^{-5}
$D+L+F+E_D+T$	UD-radius 20.5 m	Hoop	10^{-7}
	PW-height 8.0 m	Meridional	10^{-4}
$D+L+F+E_D+P_2+T$	UD-radius 20.5 m	Meridional	5.10^{-6}
	PW-height 8.0 m	Meridional	10^{-4}
$D+L+F+E_D+P_1+T$	UD-radius 20.5m	Meridional	8.10^{-4}
	PW-height 8.0 m	Meridional	10^{-2}

[x] UD = upper dome, PW = perimeter wall.

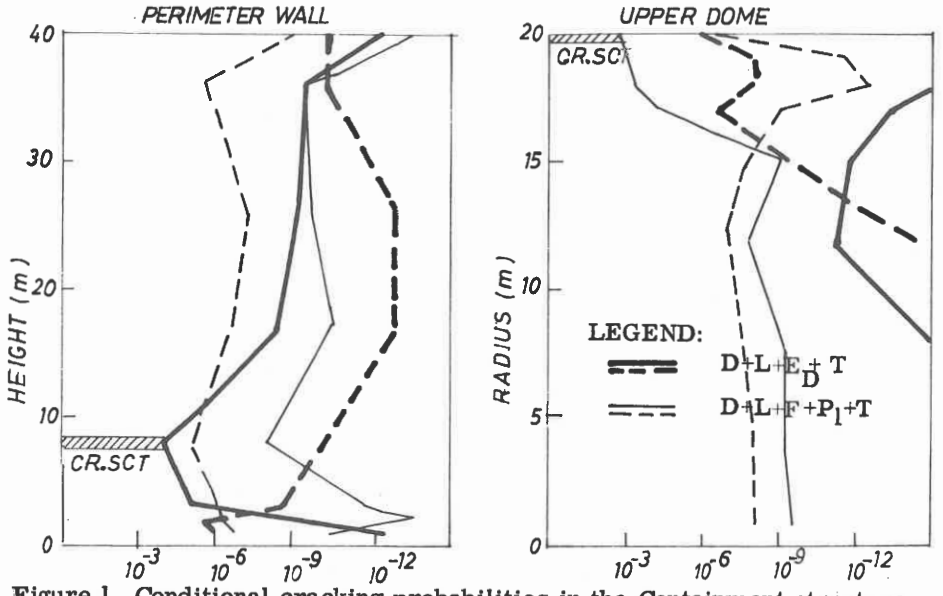

Figure 1. Conditional cracking probabilities in the Containment structure; solid lines = meridional direction, dotted line = hoop direction.

For overpressure P_3 the probability of failure is more than 90%; the through-the wall cracking with high radioactive release is surely produced. Such an event is practically avoided by multiple safety coolant systems.

The overall cracking probability at the inside, surface of the prestressed concrete containment resulted form sensitivity studies is in the range 10^{-6} - 10^{-7} ev/yr.Major contribution to the overall structural risk comes from the event combinations D+L+F+P+T or D+L+F+E+T and D+L+F+E+P+T depending on computational assumption (table 2).

Table 2. The overall cracking probability of the containment

Computational Assumptions	Major Contributor	Critical Section	Probability
Concrete creep and shrinkage have maximum effects	Earthquakes ..E.. and ..E+P.. (99%)	Perimeter Wall	1.82×10^{-6}
Concrete creep and shrinkage effects are neglected	Accidental Pressure ..P.. (55%)	Upper Dome	1.07×10^{-6}

Major contributors to the overall structural seismic risk are the extreme severe earthquakes, about 2 - 3 times the level of E_D . However, the extrapolation of hazard seismic curves in the range of very low occurence probabilities must carefully handled to avoid nonrealistic earthquake intensities for the investigated area.

The overall cracking probability is insignificantly influenced by stochastic dependencies between accidental overpressure and earthquake occurences (increase less than 1. 5 times). For through-the-wall cracking limit state, the overall failure probability was less than 10^{-7} ev/yr.

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