Probabilistic Multi-Hazard Performance Assessment of Irradiated Concrete Biological Shields and Reactor Vessel Supports

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Abstract: Prolonged operation of light-water reactors exposes the concrete biological shield (CBS) and reactor pressure vessel (RPV) supports to increased fast neutrons, degrading near-surface concrete and altering accident load transfer. In this work, a unified probabilistic framework was developed to quantify structural reliability under a loss-of-coolant accident (LOCA), a safe-shutdown earthquake (SSE), and their co-occurrence. In this study, strength limit states were formulated for the CBS and RPV support system. Capacity models informed by multi-physics, mesoscale simulations were parameterized by irradiation-induced damage depth and steel reinforcement ratio. Accident demands were represented using LOCA cavity pressures and jet forces consistent with system-level thermal-hydraulic analyses and code-based seismic base shear. Uncertainties in materials, degradation depth, and demands were represented using statistically consistent distributions, and reliability indices and failure probabilities were estimated via Monte Carlo simulation with Latin hypercube sampling. The results show that reliability decreased with increasing irradiation damage depth for all loading cases and that the combined LOCA-plus-SSE case governed performance. Increasing the reinforcement ratio improved reliability but did not maintain the ASCE 43-05 target reliability level for the more severe accident scenarios across the full range of damage depths considered. These findings support reliability-informed surveillance and life extension decisions by highlighting the importance of tracking irradiation damage depth and evaluating accident scenarios in aging plants.

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1. INTRODUCTION

Safety-related concrete structures in light-water reactors must maintain their load-carrying function during design-basis events. Two components are especially important for preserving support functions and robust load paths during extreme transients: the concrete biological shield (CBS) and the reactor pressure vessel (RPV) support load transfer region. These components can experience accidental loading from a loss-of-coolant accident (LOCA), a safe-shutdown earthquake (SSE), or a combined scenario in which both demands act concurrently [1]. Because failure in these regions can challenge safety functions and damage adjacent equipment, performance evaluation methods must quantify both margin and uncertainty in a transparent manner [2].

Extended plant operation increases the likelihood that cavity-adjacent concrete will accumulate irradiation-driven degradation, which can reduce compressive strength, tensile strength, and elastic modulus (stiffness), thereby altering governing failure modes. As degradation progresses, structural performance becomes a function of both the accident scenario and the degradation state. Deterministic checks indicate whether a component satisfies a prescribed design combination, but they do not quantify the likelihood of exceeding a limit state when materials and loads vary within realistic bounds [2].

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Therefore, a probabilistic framework to evaluate CBS and RPV support performance under LOCA, SSE, and combined loading was adopted. In this approach, a limit-state function is defined that compares a random resistance R to a random load or demand L, and failure is treated as the condition when L exceeds R [2]. The failure probability, P_f, and the reliability index, β, were used as the primary metrics for comparing cases across different limit states and load combinations [3, 4]. Efficient uncertainty propagation is especially important for nuclear structures because the probabilities of interest can be small, and direct sampling can be computationally expensive. Latin hypercube sampling (LHS) is a commonly used variance reduction technique that improves Monte Carlo efficiency for reliability problems of this type [5] and was thus adopted here.

This paper focuses on probabilistic performance under accident loads. The framework outlined herein was applied to evaluate ultimate strength limit states for irradiated concrete and anchorage / load transfer mechanisms and to estimate reliability under LOCA-only, SSE-only, and combined LOCA plus SSE demands [1, 2]. Monte Carlo simulation (MCS) with LHS was used, and the results are reported in terms of failure probabilities and reliability indices [1, 5].

2. METHODS

2.1. Reliability formulation

Safety-related nuclear structures require evaluation methods that account for uncertainty in loads, materials, and modeling assumptions. In this study, a probabilistic reliability framework was used to evaluate the CBS and RPV support system under LOCA, SSE, and combined LOCA-plus-SSE loading [1, 2]. In this framework, resistance and demand are modeled as random variables, and the probability that defined limit states are exceeded is estimated [2].

Reliability analysis compares uncertain resistance R and demand L using a limit state function. For strength-type checks, a common definition is:

$$g(\mathbf{X}) = R(\mathbf{X}) - L(\mathbf{X}), \tag{1}$$

where R is resistance, L is demand, and $\mathbf{X}$ is the vector of uncertain inputs (e.g., material strengths, loads, and modeling parameters). Failure occurs when $g(\mathbf{X}) \leq 0$, meaning demand exceeds capacity. Under this definition, the failure probability is:

$$P_f = P[g(\mathbf{X}) \leq 0] = P(R \leq L). \tag{2}$$

Limit states represent performance thresholds; ultimate states correspond to loss of load-carrying capacity, whereas serviceability states correspond to unacceptable deformation. The assessment here focuses on the ultimate performance of CBS and RPV supports under extreme LOCA and seismic demands, including a combined loading case [1, 2].

The study followed a standard reliability workflow [2, 6]:

1. **Define limit states.** Specify $g(\mathbf{X}) \leq 0$ for the failure modes of interest. For global strength checks, use $g = R - L$.
2. **Define load cases and combinations.** Three loading cases were considered in this study: (1) L_1: LOCA-only, L_{LOCA}, (2) L_2: SSE-only, L_{SSE}, and (3) L_3: a conservative combined LOCA plus SSE case in which the total demand is summed, $L_3 = L_{LOCA} + L_{SSE}$.
3. **Characterize random variables.** Assign distributions and parameters using available data and recommendations. Use unfactored nominal quantities so that the calculation targets physical failure probability rather than code-based safety margins.
4. **Propagate uncertainty and estimate probability of failure.** Use MCS with LHS. For each sample i, draw (R_i, L_i), compute $g_i = R_i - L_i$, and estimate P_f as:

$$P_f \approx \frac{1}{N}\sum_{i=1}^{N} I[\, g_i \leq 0] \tag{3}$$

where $I[\cdot]$ is the failure indicator (i.e., 1 if $g_i \leq 0$, else 0) and N is the total number of samples used in the MCS.

5. **Compute reliability index.** Failure probability P_f is converted to the reliability index $\beta = \Phi^{-1}(1 - P_f)$, where Φ^{-1} is the inverse standard normal cumulative distribution function. Larger β corresponds to lower failure probability. Cornell [4] introduced this index and Hasofer and Lind [3] later generalized it.

2.2. Structural capacity model

In this study, structural capacity for the CBS and a representative RPV shoe support was obtained from nonlinear simulations using the Lattice Discrete Particle Model (LDPM), a mesoscale concrete model developed by Cusatis et al. [7, 8]. LDPM represents concrete as interacting aggregate particles, which allows cracks to emerge naturally from the heterogeneous mesostructure [7, 8]. This capability is important because irradiation degrades cavity-adjacent concrete and alters load transfer mechanisms.

Push-over simulations of a generic shoe support configuration provided peak horizontal resistance values under combined vertical and horizontal loading. The simulations captured realistic failure mechanisms, including shear, confinement, and local crushing, enabling the reliability analysis to represent nonlinear behavior and three-dimensional stress states [7–9].

Capacity was evaluated at irradiation damage depths δ = 0, 5, 10, 15, and 20 cm for two reinforcement ratios: (1) ρ_s = 0.8%, a lightly reinforced case and (2) ρ_s = 1.6%, a reinforcement level representative of CBS and RPV supports. Mean resistance values from the LDPM simulations are summarized in Table 1 and were used as the nominal capacity in the probabilistic model. Uncertainty in resistance was represented using a coefficient of variation (COV) of 20%, which is consistent with reported scatter in degraded concrete properties and typical ranges used in nuclear structural reliability analyses [10].

Table 1: Horizontal load capacity from LDPM simulations

Damage depth δ (cm)	**Horizontal load capacity R (MN)**	
	ρ_s = 0.8%	**ρ_s = 1.6%**
0	5.28	8.64
5	5.12	8.48
10	4.64	7.68
15	4.00	6.72
20	3.04	6.08

2.3. Accident demand models

2.3.1. LOCA Loading

LOCA demands $L_1 = L_{LOCA}$ were obtained from RELAP5-3D thermal-hydraulic simulations of a generic three-loop pressurized water reactor (PWR) [11]. Peak cavity pressure differentials and jet impingement forces acting on the CBS and RPV supports were extracted from the LOCA transient [11–13]. The mean LOCA demand used in the reliability model corresponds to the maximum jet impingement force extracted from the RELAP5-3D transient and was calculated using the standard momentum flux plus pressure formulation [13]. This approach provides a physically based estimate of peak accident loads by combining system-level thermal-hydraulic response with standard jet impingement formulations, consistent with established LOCA load evaluation practices. Prior sensitivity studies have shown that predicted peak cavity pressures and differential loads can be sensitive to discharge modeling assumptions and break location [12, 13].

2.3.2. Seismic Loading

SSE demand $L_2 = L_{SSE}$ was estimated using a simplified conservative model that combines seismic ground motion with the effective weight of the RPV [14]. Spectral acceleration was converted into equivalent horizontal forces at the RPV shoe supports and distributed across the four supports using an idealized structural representation [14, 15]. This formulation yielded a conservative estimate of support-level seismic demand by directly relating spectral acceleration to equivalent inertial forces and is thus consistent with simplified code-based seismic design approaches used in nuclear structural design and assessment. The RPV mass was treated as a random variable derived from published specifications for multiple PWR designs. A lognormal distribution was used to represent manufacturing and design variability [16]. Typical SSE foundation accelerations range from 0.2g to 0.3g, according to NRC guidance [17], and values up to 0.4g–0.5g have been reported for higher seismic regions [18]. Based on those sources, a mean SSE acceleration of 0.3g was adopted for the model to represent moderate seismic conditions and to align with previous nuclear structural reliability studies [17].

2.3.3. Combined LOCA and Seismic Loading

For the combined scenario, LOCA and seismic demands were conservatively assumed to act simultaneously (i.e., $L_3 = L_{LOCA} + L_{SSE}$) so as to bound potential concurrency effects even though peak LOCA forcing and peak seismic response may not coincide in time [1, 19]. To enable consistent evaluation of uncertainty and degradation effects across cases, the demand models considered herein are intended to provide a plant-generic probabilistic comparison framework rather than a plant-specific licensing evaluation.

2.4. Uncertainty and sampling

Key inputs affecting resistance and demand were treated as random variables. Resistance and load variables were modeled using lognormal distributions to enforce non-negativity and represent the right-skew commonly observed in structural capacity and extreme load data [6, 16, 20]. Uncertainty propagation was performed using MCS with LHS. LHS improves efficiency by stratifying each variable distribution, thereby reducing estimator variance relative to simple random sampling for a fixed sample size [5]. This is particularly important because low failure probabilities require large sample sizes. Here, one million LHS samples per case were used. Table 2 summarizes the mean values and coefficients of variation (COVs) used for all random variables.

Table 2: Statistical properties of random variables

Random variable	Mean	COV (%)
Resistance R	Table 1	20 [10]
Maximum jet impingement force L_{LOCA}	6.03 MN	15 [10, 11, 13]
SSE acceleration a_s	0.3 g [17]	30 [18, 20]
RPV mass m_{RPV}	451.2 metric tons	21.5

3. Results

The reliability framework described in Section 2.1 was applied to evaluate how irradiation-driven degradation affects the accidental load performance of reinforced concrete in the RPV support load transfer region. Results are presented for the two reinforcement ratios (i.e., $\rho_s = 0.8\%$ and $\rho_s = 1.6\%$), damage depths (i.e., $\delta = 0$, 5, 10, 15, and 20 cm), and three loading cases—LOCA-only (L_1), SSE-only (L_2), and combined LOCA and SSE (L_3)—outlined previously. Both deterministic capacity–demand comparisons and probabilistic reliability metrics are used to interpret the results.

Figure 1 shows the mean resistance R as a function of irradiation damage depth δ for both reinforcement configurations, and it shows those resistance values alongside the average accident loads. The LDPM-based resistance decreases monotonically with increasing degradation depth, falling from 5.28 to 3.04 MN for $\rho_s = 0.8\%$ and from 8.64 to 6.08 MN for $\rho_s = 1.6\%$ as δ increases from 0 to 20 cm. The deterministic comparison indicates that SSE-only loading (L_2) remains well below the mean resistance for most cases, whereas LOCA-only loading (L_1) produces smaller safety margins. The combined LOCA and SSE case (L_3) approaches or exceeds the mean resistance at relatively small degradation depths.

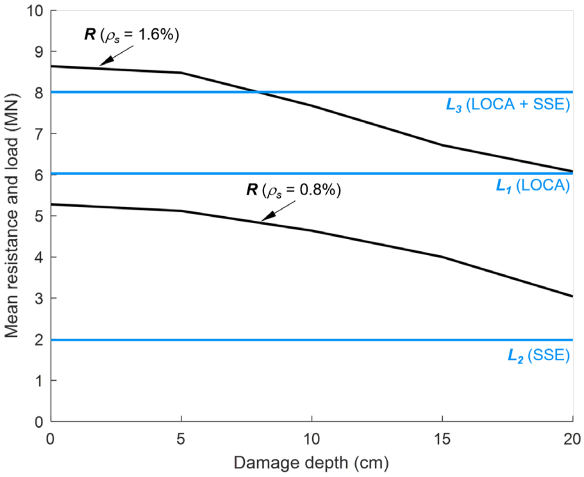
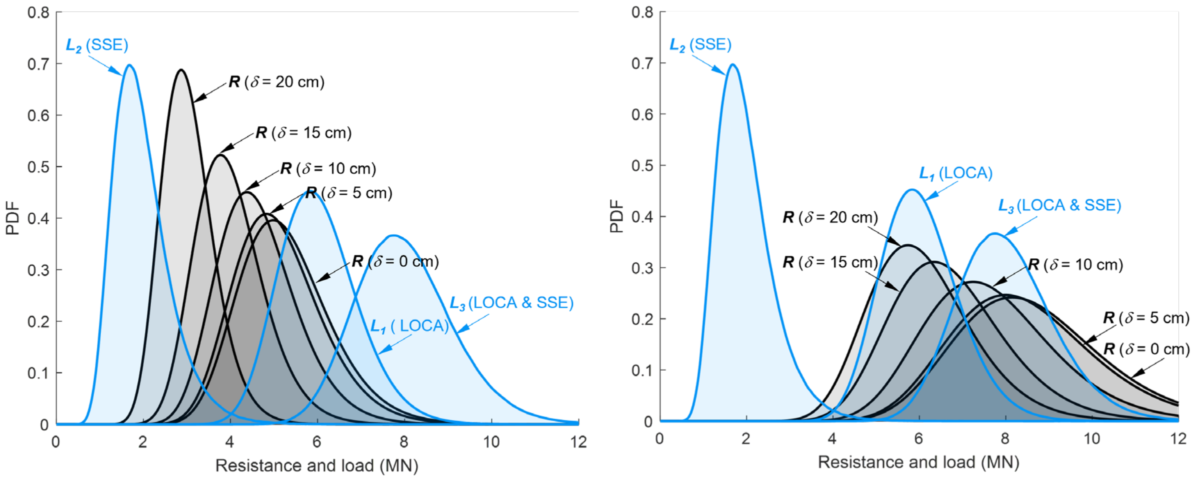


Figure 1: Mean resistance R versus damage depth δ for $\rho_s = 0.8\%$ and $\rho_s = 1.6\%$; blue horizontal lines show mean accident loads (L_1, L_2, L_3)

The evolution of resistance and load probability density functions (PDFs) is shown in Figure 2. As irradiation damage increases, the resistance distributions shift toward lower values due to degradation of the load transfer region, and the load distributions remain unchanged. As shown in Figure 2a, for $\rho_s = 0.8\%$, the resistance distributions progressively approach and overlap the LOCA-only (L_1) and combined LOCA and SSE (L_3) distributions, indicating increasing failure likelihood. Increasing the reinforcement ratio to $\rho_s = 1.6\%$ shifts the resistance distributions toward higher values and reduces the overlap with the load distributions, particularly for SSE-only loading (L_2), as illustrated in Figure 2b.



(a) **(b)**

Figure 2: Resistance PDFs at δ = 0–20 cm (black) and load PDFs for L_1, L_2, and L_3 (blue) for (a) $\rho_s = 0.8\%$ and (b) $\rho_s = 1.6\%$

The resulting failure probabilities P_f are summarized in Tables 3 and 4. Figure 3 shows that reliability decreases monotonically with increasing damage depth for all loading cases. For $\rho_s = 0.8\%$, reliability is low across all scenarios; β decreases from approximately 2.64 to 1.21 for SSE-only loading (L_2) and becomes negative for LOCA-only (L_1) and combined LOCA and SSE (L_3) loading at most damage depths. Increasing the reinforcement ratio to $\rho_s = 1.6\%$ significantly improves reliability but does not eliminate the governing influence of severe loading. For SSE-only loading (L_2), β decreases from 3.87 at $\delta = 0$ cm to 3.00 at $\delta = 20$ cm, whereas LOCA-only (L_1) and combined LOCA and SSE (L_3) loading produce substantially lower reliability. Compared with the ASCE 43-05 target reliability level $\beta \geq 3.719$ (equivalent to $P_f \leq 10^{-4}$) for safety-related nuclear structures, the $\rho_s = 0.8\%$ configuration is noncompliant for all cases ($L_1 - L_3$), while the $\rho_s = 1.6\%$ configuration satisfies the target only for SSE-only loading (L_2) at small damage depths [14].

Table 3: Probability of failure P_f for $\rho_s = 0.8\%$ under L_1, L_2, and L_3 loading

Loading case	Damage depth δ (cm)				
	0	5	10	15	20
L_1 (LOCA)	7.16×10^{-1}	7.56×10^{-1}	8.62×10^{-1}	9.54×10^{-1}	9.97×10^{-1}
L_2 (SSE)	4.21×10^{-3}	5.22×10^{-3}	1.03×10^{-2}	2.70×10^{-2}	1.13×10^{-1}
L_3 (LOCA + SSE)	9.61×10^{-1}	9.71×10^{-1}	9.89×10^{-1}	9.98×10^{-1}	1.00

Table 4: Probability of failure P_f for $\rho_s = 1.6\%$ under L_1, L_2, and L_3 loading

Loading case	Damage depth δ (cm)				
	0	5	10	15	20
L_1 (LOCA)	7.82×10^{-2}	9.00×10^{-2}	1.74×10^{-1}	3.44×10^{-1}	5.00×10^{-1}
L_2 (SSE)	5.40×10^{-5}	5.70×10^{-5}	1.47×10^{-4}	5.76×10^{-4}	1.35×10^{-3}
L_3 (LOCA + SSE)	3.93×10^{-1}	4.23×10^{-1}	5.85×10^{-1}	7.78×10^{-1}	8.82×10^{-1}

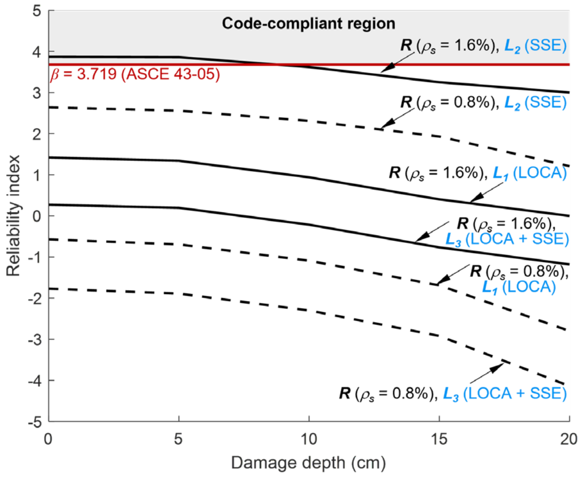


Figure 3: Reliability index β versus damage depth δ for $\rho_s = 0.8\%$ (dashed) and $\rho_s = 1.6\%$ (solid) under L_1, L_2, and L_3; the red line indicates the ASCE 43-05 target $\beta = 3.719$, with the shaded region showing code-compliant reliability

These results show that irradiation damage in the CBS load transfer region can significantly reduce structural reliability under accident loading, particularly for combined LOCA and seismic demands. Increasing reinforcement improves reliability but does not fully offset the loss of capacity at large damage depths, which indicates that additional design margins or alternative load transfer strategies may be required to meet reliability targets for safety-related nuclear structures [14].

4. CONCLUSION

In this work, a probabilistic framework was developed to evaluate the reliability of irradiated CBS and RPV support load transfer regions under LOCA, SSE, and combined LOCA and SSE loading. Results show that structural capacity and reliability decrease as irradiation damage depth increases and that the combined LOCA and SSE case governs performance. Increasing reinforcement from $\rho_s = 0.8\%$ to $\rho_s = 1.6\%$ improves reliability but does not maintain the ASCE 43-05 target reliability level $\beta \geq 3.719$ ($P_f \leq 10^{-4}$) for the more severe accident scenarios [14]. The $\rho_s = 0.8\%$ configuration is noncompliant for all loading cases, whereas the $\rho_s = 1.6\%$ configuration satisfies the target only for SSE-only loading at small damage depths. These results indicate that irradiation damage in cavity-adjacent concrete can significantly affect the reliability of safety-related load transfer regions in aging reactors and should be explicitly considered in structural assessments and life extension decisions.

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