A Practical Reliability-Based Design Code Calibration For Concrete Containment Structures

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ABSTRACT

This paper develops a probability-based load combination criterion for R.C. nuclear containment structures in Korea. A FEM-based random vibration analysis and an advanced 2nd moment reliability method are used for the assessment of limit state probabilities of containment structures under the earthquake and accidental loads. The use of the serviceability limit state of the crack failure is suggested as a critical failure criterion of concrete containment structures.

1. INTRODUCTION

In Korea, more than 10 units of nuclear power plants were constructed so far and a number of more units are under design or planning stage. However, the current design criteria and the design loads for nuclear power plants are not probability-based and similar to those of the USA. The stochastic nature of natural hazard or accidental loads and the variations of material properties dictate a probabilistic approach to be used for a rational assessment of structural safety and performances. The paper is intented to develop a probability-based load criterion in the form of LSD code for concrete containment structures, and to show how recently developed stochastic and advanced structural reliability methods can be systematically applied for the estimations of the limit state probabilities of containmnet structures under stochastic dynamic loads such as earthquakes and LOCA loads. Thus, the approaches and the methods for the reliability analysis and calibration of the load combinations for the design of nuclear containment structures represented herein are similar to the reference [Shinozuka et al, 1987]. But, in the paper, the use of the serviceability limit state of the crack failure that causes the emission of radioactive materials is suggested as a critical failure criteria of concrete containment structures.

2. PROBABILISTIC MODEL FOR LOAD AND RESISTANCE

2.1 Load Model

A concrete containment structure will be subjected to various random static and stochastic loads during lifetime. Since loads involve inherent randomness and other uncertainties, an appropriate probabilistic model for each load must be established in order to perform reliability analysis. In this study, the dead load and the operational live load are assumed to be static and deterministic, because the uncertainties in these loads are negligible compared to other major dynamic loads such as earthquake and thus the effect of these loads on the limit state probability is minor. The structural design of the earthquake loads and the seismic hazard aseessment in Korea have been reported by a number of investigators [Yu,1987]. Based on the available data in Korea, the earthquake load in terms of the ground acceleration was modeled as a zero-mean stationary Gaussian process with a finite duration, described by a Kanai-Tajimi power spectral density $S_g(\omega)$ [Kanai,1957] :

$$S_g(\omega) = \frac{1 + 4\zeta_g^2(\omega/\omega_g)^2}{[1-(\omega/\omega_g)^2]^2 + 4\zeta_g^2(\omega/\omega_g)^2} S_0 \qquad (1)$$

where S_0 is a random variable which represents the intensity of an earthquake. ω_g and ζ_g denote the dominant ground frequency and the ground damping ratio, which depend on the local soil conditions. The earthquake parameters for the nuclear power plants in Korea are summarized in Table 1.

Table 1 Parameters of Earthquake Model

Items	**sample I**	**sample II**	**sample III**
$a_{SSE}(g)$	0.20	0.25	0.31
ω_g	5π	9π	9π
ζ_g	0.6	0.6	0.6
μ_{dE}	10	10	10
a_0	0.05	0.05	0.05
$a_{\max}$	$2a_{SSE}$	$2a_{SSE}$	$2a_{SSE}$

The accidental pressure load due to relatively rare event LOCA is considered as a quasi-static load and assumed as uniformly distributed on the containmnet wall, which was modeled as a Poisson rectangular pulse process, having specified mean occurence rates and duration during the containment life. The parameters for the accidental pressure load are shown in Table 2.

Table 2 Parameters of Accidental Load

Items	**CASE I**	**CASE II**	**CASE III**
λ_p	1.0×10^{-5} / yr	1.0×10^{-4}/ yr	1.0×10^{-5}/ yr
μ_{dp}	600	1200	1200
Mean / Design	0.9	0.83	0.88
C.O.V.	0.12	0.16	0.20

2.2 Resistance Model

Probabilistic description of structural resistance is also necessary for the reliability assessment of nuclear containment structures. The geometry of the containment is assumed to be deterministic, while the material strength is considered as random variables. Based on the statistical data available in Korea, the concrete compressive strength and the yield strength of reinforcing steels are assumed to follow Gaussian distributions with the parameters as shown in Table 3.

Table 3 Parameters of Materials

Items	Strength(psi)	C.O.V.	Distribution	Remark
Concrete	6000	0.200	Gaussian	91 day
Re-Bar	60000	0.124	Gaussian	ASTM Grade 60

3. LIMIT STATE MODELS

For the calibration of load criteria for the design of containment structures a serviceability limit state of the crack failure is considered, which causes the emission of radioactive materials, instead of the ultimate strength limit state of flexural failure. The crack failure limit state condition can be equivalently expressed in terms of the stress limit of the reinforcement bars as

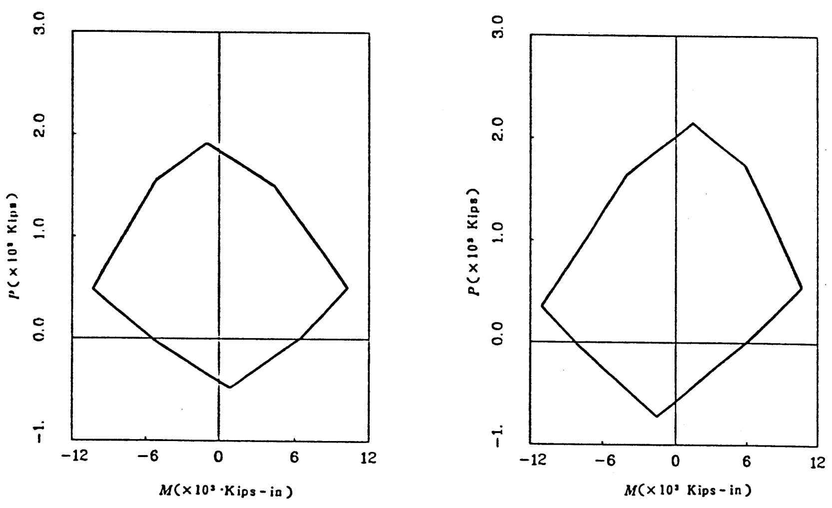
$$f_s - f_{sc} \geq 0 \tag{2}$$

where f_s is the stress in the reinforcement bars f_{sc} is the critical stress corresponding to the crack limit of the containment walls. f_{sc} can be derived in the following form [ACI,1988].

$$f_{sc} = \frac{2.5\,\omega}{k\beta\sqrt{d_{b1}s_2/\rho_{t1}}} \tag{3}$$

where ω is the crack width on the surface of the containment walls reinforced by deformed bars.

On the basis of the above definition of the limit state, the corresponding limit state surface can be constructed in terms of the membrane stress and bending moment. A typical limit state surface is shown in Fig. 1 .



X – Direction

Y – Direction

Fig.1 Limit State Surface

4. LIMIT STATE PROBABILITY

A three-dimensional finite element model is used for the random vibration analysis [Shinozuka et al, 1984] of the containment structures. The containment is divided into 21 layers. The discretization required a total of 505 nodes and 492 elements. On the basis of the FEM-based random vibration analysis, the limit state probability values are computed. Limit state probabilities were estimated for the following load combinations.

$$
\begin{aligned}
&D + L + P \\
&D + L + E \\
&D + L + P + E
\end{aligned}
\tag{4}
$$

where D = dead load, L = live load, P = accidental pressure load, E = earthquake load.

In order to evaluate the structural reliability of the containment structure, first, the critical element specific to each load combination must be identified. The limit state probability of the containment as a whole and the limit state probabilities under various load combinations are summarized in Table 4.

Table 4 Limit State Probability

Load Combination	Critical Height	Direction	Limit State Probability
D+L+P	11.5 m	Hoop	2.905×10^{-4}
D+L+E	Bottom	Meridional	1.962×10^{-4}
D+L+P+E	11.5 m	Hoop	1.161×10^{-10}
Overall	.	.	4.867×10^{-4}

It can be observed from Table 4 that the value of the mean coincidence rate of occurrence of earthquake plus pressure is smaller than accidental pressure or earthquake. Thus, the contribution to the overall limit state probability due to a coincidence of earthquake and accidental pressure is negligible. Hence, it is reasonable not to design concrete containment structures for this rare event.

5. CALIBRATION OF LOAD FACTORS

The load factors are calibrated by using an iterative hearistic optimization technique, selecting a set of $\gamma_i's$ that minimize the function with a set of fixed resistance factor $\phi=0.85$. The closeness is measured by an objective function defined as follow.

$$
I(\gamma_i) = \sum_{i=1}^{n} \omega_i (\log P_{fi} - \log P_{fo})^2 \tag{5}
$$

in which P_{fi} is the limit state probability for the i-th sample containment, P_{fo} is the target limit state probability and ω_i is a weight factor for i-th sample containment. The minimum value of objective function $I(\gamma)$ occurs when γ is optimal.

The dead load factor γ_D is preset to be 0.9, because the dead load effect counteracts the effect due to accidental pressure. Target limit state probability is assumed to be one of the 3 values: 1×10^{-5}, 1×10^{-6} and 1×10^{-7} for a design lifetime of 40 years.

For the case of (D+L+P) load combination , the limit state probabilities during lifetime were computed as shown in Table 5, and the corresponding objective functions are plotted in Fig. 2. The objective function I is computed at several values of γ_p and these values are shown in Fig. 2. It can be seen from Fig. 2 that minimum value of objective function results in near γ_p = 1.3 for $P_{fo} = 1\times10^{-6}$.

Table 5 Limit State Probability (D+L+P)

γ_p	Case I	Case II	Case III
1.0	0.1083×10^{-03}	0.1394×10^{-03}	0.1609×10^{-03}
1.1	0.2756×10^{-04}	0.5820×10^{-04}	0.8776×10^{-04}
1.2	0.3213×10^{-05}	0.1748×10^{-04}	0.3883×10^{-04}
1.3	0.2089×10^{-06}	0.3597×10^{-05}	0.1393×10^{-04}
1.4	0.5005×10^{-08}	0.4578×10^{-06}	0.3585×10^{-05}
1.5	0.7885×10^{-10}	0.3863×10^{-07}	0.8974×10^{-06}
1.6	0.4559×10^{-12}	0.1864×10^{-08}	0.1358×10^{-06}

For the case of (D+L+E) load combination, limit state probabilities were computed as shown in Table 6, and the the objective function vs. γ_E are shown in Fig. 3. It can be seen from Fig. 3 that minimum value of objective function results in near $\gamma_E = 1.2$ for $P_{fo} = 1\times10^{-6}$.

Table 6 Limit State Probability (D+L+E)

γ_E	Sample I	Sample II	Sample III
1.0	0.4366×10^{-05}	0.1189×10^{-03}	0.2225×10^{-02}
1.1	0.4370×10^{-06}	0.3583×10^{-04}	0.1371×10^{-02}
1.2	0.6142×10^{-07}	0.1043×10^{-04}	0.7379×10^{-03}
1.3	0.7234×10^{-08}	0.2683×10^{-05}	0.3484×10^{-03}
1.4	0.7118×10^{-09}	0.6174×10^{-06}	0.1481×10^{-03}
1.5	0.6023×10^{-10}	0.1265×10^{-06}	0.5808×10^{-04}
1.6	0.4094×10^{-11}	0.2342×10^{-07}	0.2096×10^{-04}
1.7	0.2371×10^{-12}	0.3734×10^{-08}	0.7020×10^{-05}
1.8	0.1204×10^{-13}	0.5465×10^{-09}	0.2186×10^{-05}

The proposed load combinations for design of the concrete containment structure in Korea are as follow ;

$$\begin{aligned} &0.9D + L + 1.3P_a \\ &1.2D + L + 1.2E_{ss} \qquad (6) \\ &0.9D + L - 1.2E_{ss} \end{aligned}$$

This load combinations are different from those in ASME code or in the reference [Shinozuka et al, 1987].

This paper calculated the load combination criteria for strength limit state, too. The results of load combination criteria for strength limit state are similar to those for the serviceability limit state.

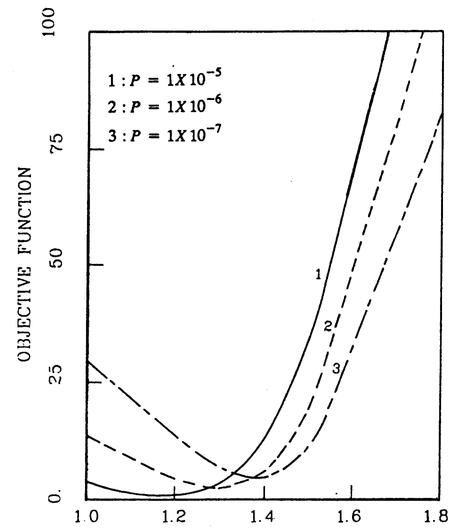


Fig. 2 Load Factor γ_p

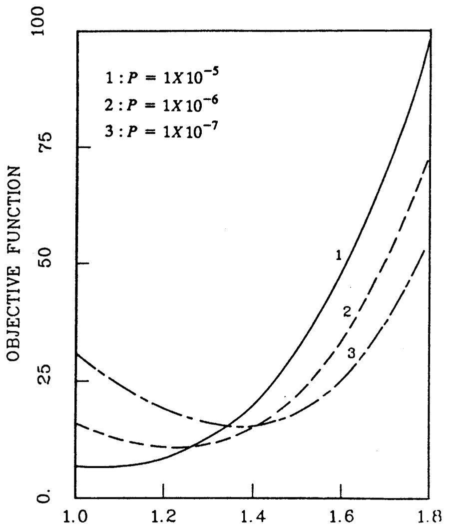


Fig. 3 Load Factor γ_E

6. CONCLUSION

This study presented a practical load combination criteria for designing concrete containment structures. In this paper, the use of the serviceability limit state of the crack failure that causes the emission of radioactive materials is suggested as a critical failure criteria of concrete containment. The purpose of constructing concrete containment structure is to protect radioactive release, and so the serviceability limit state is more reasonable than the strength limit state. Load factors are selected on the basis of serviceability limit state and target limit state probability. The load factor for accidental pressure $\gamma_p = 1.3$ and earthquake ground acceleration $\gamma_E = 1.2$ for $P = 1 \times 10^{-6}$ are appropriate for nuclear containment structures in Korea.

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