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Serviceability design load factors for reinforced concrete containment structures

Han, B.K.[1], Ang, A.H-S.[2]
1) Seoul National Polytechnic University, Dept. of Structural Engineering, Seoul, Korea
2) University of California, Dept. of Civil & Environmental Engineering, Irvine, CA, U.S.A.

ABSTRACT : The current ASME code for reinforced concrete containment structures are not based on probability concepts. The paper develops probability-based load factors for the limit state design of reinforced concrete containment structures. Load factors for the design of reinforced concrete containment structures are proposed. The proposed load factors are examined in terms of a set of code performance objectives and consistency in limit state probability.

1 INTRODUCTION

The current ASME code design load factors for reinforced concrete containment structures are not based on probability concepts. The stochastic nature of natural hazard or accidental loads and the variations of material properties dictate a probabilistic approach for a rational assessment of structural safety and performance. In recent years, reliability analysis and reliability-based design of reinforced concrete containment structures have been developed by Ang (1991), Shinozuka (1983) and Schuëller (1989).

The paper develops probability-based load factors for the limit state design of reinforced concrete containment structures, and demonstrates how recently developed stochastic and advanced structural reliability methods can be systematically applied for the estimation of the limit state probabilities of containment structures under stochastic dynamic loads such as accidental pressure and earthquakes loads.

The use of the serviceability limit state of crack failure that can cause the emission of radioactive materials is suggested as a critical failure criterion for reinforced concrete containment structures.

2 CONTAINMENT LOADS AND MATERIAL PROPERTIES

A reinforced concrete containment structure is subjected to various random static and stochastic loads during its lifetime. Since these loads involve inherent randomness and other uncertainties, an appropriate probabilistic model for each load must be established in order to perform reliability analysis.

The dead load is the weight of the containment structure itself. The unit weight of reinforced concrete is taken to be 2,400 kg/m^3. The dead load is static and assumed to be deterministic. There are some uncertainties as to the magnitude of the live load. But it is assumed to be static and deterministic, because the uncertainties in these loads are negligible compared to other major dynamic loads such as earthquake and the effect of these loads on the limit state probability is minor.

The accidental pressure loads due to relatively rare occurrence of LOCA are assumed to be quasi-static loads that are distributed uniformly on the reinforced concrete containment wall. The occurrence of accidental pressure loads is modeled as a Poisson rectangular pulse process, having specified mean occurrence rates and duration during the lifetime of the structure. The load intensities are assumed to be Gaussian.

The earthquake ground acceleration can be represented by an amplitude modulated nonstationary random process with an instantaneous power spectral density function $S(\omega)$. The earthquake load in terms of the ground acceleration is modeled as a zero-mean stationary Gaussian process with a finite duration, described by a Kanai-Tajimi power spectral density $S(\omega)$ [Tajimi 1960] :

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

The Kanai-Tajimi spectrum is obtained by filtering a white noise through a second order linear filter; physically the Kanai-Tajimi spectrum represents the response of a single degree of freedom system to a white noise base excitation. The Kanai-Tajimi spectrum, however, gives unrealistic and erroneous ground velocity and displacement responses at low frequencies, which could strongly influence the dynamic responses of inelastic systems. This shortcoming can be corrected through a high-pass filter suggested by Clough-Penzien [Clough 1975] resulting in the follows spectrum.

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

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 ground damping ratio, which depend on the local soil conditions.

Probabilistic description of material properties are also necessary for the reliability assessment of nuclear containment structures. The geometry of the containment is assumed to be deterministic, whereas the material strength is considered as a random variable. Based on statistical data, the concrete compressive strength is assumed to be Gaussian distribution with a mean value of 41.2 MPa and COV of 0.14, and the yield strength of ASTM A 615 Grade 60 reinforcing steels is assumed to have a lognormal distribution with a mean value of 489.5 MPa and COV of 0.11.

3 SERVICEABILITY LIMIT STATE MODELS

The limit state is considered to have occurred if the crushing strength of the concrete is reached at the extreme fiber of the wall cross-section and/or if the reinforcing bars begin to yield. The purpose of constructing reinforced concrete containment structure is to protect radioactive release, and so the use of the serviceability limit state against crack failure that can cause the emission of radioactive materials is suggested as a critical failure criterion for reinforced concrete containment structures. For the calibration of load criteria for the design of containment structures a serviceability limit state against crack failure is considered, 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 as

$$(3) \qquad f_s \geq f_{sc}$$

where f_s is the stress in the reinforcing bars, f_{sc} is the critical stress corresponding to the crack limit of the containment walls. The cracking mechanism in the containment wall is controlled primarily by the steel stress level and the spacing of the reinforcement in the two perpendicular directions. In addition, the clear concrete cover in a containment wall is nearly constant, whereas it is a major variable in the crack control equations for the beams. Analysis of data on cracking in cylindrical wall has provided the following equation for predicting the maximum crack width [Nawy 1972]:

$$(4) \qquad w = k\beta f_s \sqrt{d_{b1} s_2 / \rho_{t1}}$$

where the radical $\Gamma_1 = d_{b1} s_2 / \rho_{t1}$ is termed the grid index, and can be transformed into

$$(5) \qquad \Gamma_1 = \left[\frac{s_1 s_2 d_c}{d_{b1}} \frac{8}{\pi}\right]$$

in which k is the fracture coefficient, β is 1.25, f_s is actual average service load stress or 40 percent of the design yield strength f_y, d_{b1} is diameter of the reinforcement in direction "1" closet to the concrete outer fibers, s_2 is the spacing of the reinforcement and ρ_{t1} is the active steel ratio.

Therefore f_{sc} can be derived in the following form.

$$(6) \qquad f_{sc} = \frac{2.5\, w}{k\beta \sqrt{d_{b1} s_2 / \rho_{t1}}}$$

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

4 SERVICEABILITY LIMIT STATE PROBABILITY

In order to perform reliability analysis, a set of representative containment structures must be selected. The design parameters include the containment geometry and material strengths. In this study, representative values of the design parameters are shown in Fig. 1. A three-dimensional finite element model is used for the random vibration analysis of the containment structures. The containment is divided into 21 layers as shown in Fig. 2. The discretization required a total of 505 nodes and 492 elements.

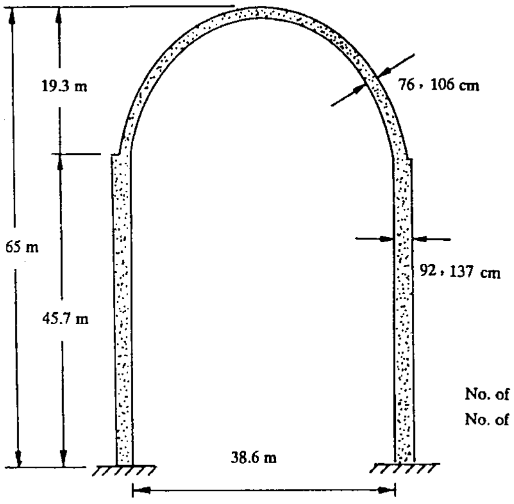

Fig. 1 Feature of containment structures

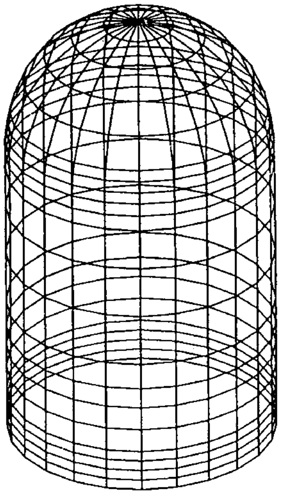

Fig. 2 Three dimensional finite element model

On the basis of the FEM-based random vibration analysis, the limit state probabilities are computed. This study is mainly concerned with the reliability analysis of reinforced concrete containment structures for serviceability limit state. The serviceability limit state probabilities were estimated for the D+L+P and D+L+E load combinations, which can be written as

$$(7) \qquad P_f = P_{f_{(D+L)}} + P_{f_{(D+L+P)}} + P_{f_{(D+L+E)}}$$

On the right-hand side, each term can be written as

$$(8) \qquad P_{f(c)} = \lambda_{(c)} \cdot T \cdot P_{f/(c)}$$

where $\lambda_{(c)}$ is the rate of occurrence of the load combination (c), T is the lifetime of the reinforced concrete containment structure, and $P_{f/(c)}$ is the conditional limit state probability.

5 PROBABILITY-BASED LOAD FACTORS

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

$$(9) \qquad I(\gamma_i) = \sum_{i=1}^{n} (\log P_{fi} - \log P_{fo})^2$$

in which P_{fi} is the limit state probability for the i-th sample containment and P_{fo} is the target limit state probability. The minimum value of the objective function $I(\gamma_i)$ occurs when γ_i is optimum.

Various loads act on a reinforced concrete containment structure. The loads involve randomness and uncertainties. The parameters for the accidental pressure load are shown in Table 1.

Table 1 Parameters of accidental load

Parameters	Case I	Case II	Case III
λp (yr)	1.0×10^{-4}	1.0×10^{-5}	1.0×10^{-5}
μ_{dE} (sec)	600	600	1200
Mean/Design	0.9	0.88	0.83
C. O. V.	0.12	0.16	0.2

The structural designs for the earthquake loads and the seismic hazard assessment in Korea have been reported. [Yu 1987] Based on the available data for Korea, the earthquake parameters for nuclear power plants are assumed to be those shown in Table 2.

Table 2 Parameters of earthquake load

Parameters	Sample I	Sample II	Sample III	Sample IV	Sample V
a_{SSE}	0.2 g	0.25 g	0.28 g	0.32 g	0.16 g
ω_g	8π	5π	8π	8π	8π
ζ_g	0.6	0.6	0.6	0.6	0.6
p_g	3	3	3	3	3
μ_{dE} (sec)	10	10	10	20	20
λ_E	0.0147	0.0263	0.0353	0.0499	0.0082

Target limit state probability is assumed to be one of the 3 values: 2.5×10^{-8}, 1.0×10^{-8} and 2.5×10^{-9} per year (1.0×10^{-6}, 4.0×10^{-7} and 1.0×10^{-7} for a design lifetime of 40 years). [Cave 1991] The dead load factor γ_D is preset to be 1.2 or 0.9 as in the A58 Standard. [Ellingwood 1980]

For the case of (D+L+P) load combination, the live load factor is taken as zero, because the live load has a stabilizing effect. The limit state probabilities during the lifetime were computed as shown in Table 3. The optimum objective function values and corresponding load factors are computed in Table 5.

For the case of (D+L+E) load combination, the companion live loads in conventional structures has shown that it is reasonable to preassign a live load factor of 1.0. The limit state probabilities were computed as shown in Table 4. The optimum objective function values and corresponding load factors are computed in Table 5.

Table 3 Serviceability limit state probability (/yr)
(0.9 D + $\gamma_p P_a$)

γ_p	Case I	Case II	Case III
1.0	2.7075×10^{-6}	3.4850×10^{-6}	4.0225×10^{-6}
1.1	6.8900×10^{-7}	1.4450×10^{-6}	2.1940×10^{-6}
1.2	8.0325×10^{-8}	4.3700×10^{-7}	9.7075×10^{-7}
1.3	5.2225×10^{-9}	8.9925×10^{-8}	3.4825×10^{-7}
1.4	1.2513×10^{-10}	1.1445×10^{-8}	8.9625×10^{-8}
1.5	1.9713×10^{-12}	9.6575×10^{-10}	2.2435×10^{-8}
1.6	1.1398×10^{-14}	4.6600×10^{-11}	3.3950×10^{-9}

Table 4 Serviceability limit state probability (/yr)
(1.2 D + 1.0 L + $\gamma_{ES} E_{ss}$)

γ_{ES}	Sample I	Sample II	Sample III	Sample IV
1.0	6.1175×10^{-6}	2.7225×10^{-6}	1.2683×10^{-4}	5.5625×10^{-5}
1.1	2.4802×10^{-6}	8.9575×10^{-7}	1.0130×10^{-4}	3.4275×10^{-5}
1.2	8.8775×10^{-7}	2.6075×10^{-7}	7.6000×10^{-5}	1.8448×10^{-5}
1.3	2.8450×10^{-7}	6.7075×10^{-8}	5.1800×10^{-5}	8.7100×10^{-6}
1.4	8.2100×10^{-8}	1.5435×10^{-8}	3.1650×10^{-5}	3.7025×10^{-6}
1.5	2.1748×10^{-8}	3.1625×10^{-9}	1.7528×10^{-5}	1.4520×10^{-6}
1.6	5.1000×10^{-9}	5.8550×10^{-10}	8.9250×10^{-6}	5.2400×10^{-7}
1.7	1.0935×10^{-9}	9.3350×10^{-11}	4.2125×10^{-6}	1.7550×10^{-7}
1.8	2.1768×10^{-10}	1.3663×10^{-11}	1.8698×10^{-6}	5.4650×10^{-9}

6 PROPOSED LOAD FACTORS AND RELIABILITY ASSESSMENTS

The load factors specified in the ASME code are $\gamma_p = 1.5$ (abnormal environment) and $\gamma_{ES} = 1.0$ (extreme environment). [ACI-ASME 1980]

The load factors proposed herein for design of the reinforced concrete containment structures are shown in Table 5. Note that these load factors are different from those in the ASME code.

Table 5 Optimum object function values and proposed load factors

Target limit state	Accidental load			Earthquake load		
probability (/yr)	Optimum I(γ_p)	γ_p	Proposed	Optimum I(γ_{ES})	γ_{ES}	Proposed
2.5×10^{-8}	2.045	1.288	1.3	10.579	1.533	1.5
1.0×10^{-8}	3.163	1.328	1.3	11.631	1.597	1.6
2.5×10^{-9}	4.360	1.380	1.4	13.394	1.721	1.7

Reliability assessments of the containment structures shown, Table 6, are carried out using the probabilistic descriptions of load and material for $P_{fo} = 1.0 \times 10^{-8}$ per year. Table 6 shows the design of two sample reinforced concrete containment structures using the ASME code and the proposed load factors. The total limit state probabilities for the two sample containments designed according to the ASME code are quite different. But the total limit state probabilities for the two sample containments designed according to the proposed load factors are much more uniform. The proposed load factors, therefore, should give designs with more consistant safety levels than the ASME code.

Table 6 Result of reliability assessments

Design Criteria	Load combination	Case III, Sample IV	Case III, Sample V
ASME	$D+L+1.5P_a$	2.302×10^{-8}	2.244×10^{-8}
	$D+L+E_{ss}$	4.813×10^{-5}	3.403×10^{-8}
	total	4.815×10^{-5}	5.647×10^{-8}
This Study	$0.9D+1.3P_a$	3.538×10^{-7}	3.483×10^{-7}
	$1.2D+L+1.6E_{ss}$	5.240×10^{-7}	3.870×10^{-9}
	total	8.778×10^{-7}	3.521×10^{-7}

7 CONCLUSION

This study is based on the use of the serviceability limit state against crack failure to prevent the emission of radioactive materials as a critical criterion for the design of reinforced concrete containment structures. The purpose of constructing reinforced concrete containment structure is to protect against radioactive release, and so the serviceability limit state is an essential condition or requirement for design.

Load factors for limit state design of reinforced concrete containment structures are suggested. These load factors are determined on the basis of serviceability limit state and specified target limit state probability. The load factors are summarized in Table 5 for the target limit state probabilities of $P_{f0} = 2.5 \times 10^{-8}$, 1.0×10^{-8} and 2.5×10^{-9} per year.

The proposed load factors were proved to be in accordance with a set of code performence objective and showed consistency in the limit state probability. The proposed load factors, therefore, should give designs with more consistant safety levels than the ASME code.

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