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Reliability Assessments and Design Load Factors for Reinforced Concrete Containment Structures of Nuclear Power Plant

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Abstract

The current ASME code 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 require a probabilistic approach for a rational assessment of structural safety and performance.

The paper develops design load factors for the serviceability limit state of reinforced concrete containment structures. The target limit state probability is determined and the load factors are calculated by the numerical analysis. Design load factors are proposed and carried out the reliability assessments.

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 nuclear structures have been developed. [1-8]

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.

In this study, the Clough-Penzien power spectral density and the serviceability limit state is considered instead of the Kanai-Tajimi spectrum and the ultimate strength limit state of flexural failure in the reference.

The target limit state probability is determined and the load factors are calculated by the numerical analysis. Load factors for the design of reinforced concrete containment structures are proposed. The proposed load factors are also examined in terms of a set of code performance objectives and consistency in limit state probability. Reliability assessments of the containment structures are carried out using load combination criteria.

2. Containment Loads and Material Properties

2.1. Containment Loads

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/m³. 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. 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. In this study, for the calculation of power spectral density Clough-Penzien is consider in the follow spectrum [9] :

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

where S_0 is a random variable which represents the intensity of an earthquake. The values ω_g and ζ_g denote the dominant ground frequency and ground damping ratio, which depend on the local soil conditions. The frequency parameter ω_f and the damping parameter ζ_f are selected to give the desired filter characteristics.

2.2. Material Properties

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.

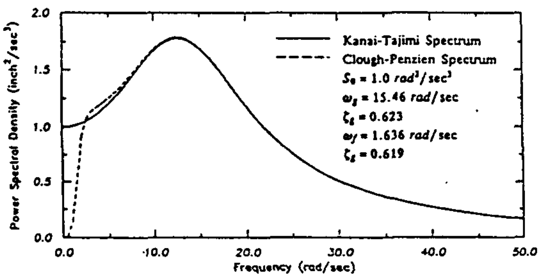

Fig.1 Kanai-Tajimi and Clough-Penzien Power Spectra.

[3,13]

3. Serviceability Limit State Models

A limit state is defined as a state of undesirable structural behavior. For the calibration of load criteria for the design of containment structures a flexural strength limit state is considered. The strength limit state for containment structures may be defined as ultimate collapse failure of reinforced concrete. 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.[12]

The crack failure limit state condition can be equivalently expressed in terms of the stress limit of the reinforcement as

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

where f_s is the stress in the reinforcing bars, f_{sc} is

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

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.[10]

where w is the crack width on the surface of the containment walls reinforced by deformed bars. k is the fracture coefficient, β is ratio of distances from tension face and from steel centroid to neutral axis, 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.

However, the state of the critical crack width and depth which triggers the emission of radioactive materials [7] cannot be defined precisely, and relevant test data of the critical crack are not yet available.

Table 1. Representative Values of Design Parameters

Design Parameters	Design Range	This Study
Cylindrical wall height	44 - 49 m	46 m
Cylindrical wall thickness	90~150 cm	92 cm, 137 cm
Wall inside radius	18~23 m	19.5 m
Dome rise ratio	1.0	1.0
Deme thickness	76 - 106 cm	76 cm, 106 cm
Concrete compressive strength	20.6-34.3 MPa	27.5-34.3 MPa
Steel yield strength	412 MPa	412 MPa

On the basis of the above definition of the serviceability limit state, the corresponding limit state surface can be constructed in terms of the membrane stress and bending moment. The serviceability limit state surface consists of the segments of the following eight straight lines which define the octagonal area. [12]

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 listed in Table 1.

A three dimensional finite element model is used for the random vibration analysis of the containment structures.

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 linear FEM analysis can be used to compute the limit state probability. If the limit state probability is related to the various ultimate strength limit states, nonlinear FEM analysis would be required. The serviceability limit state probabilities were estimated for the D+L+P and D+L+E load combinations.

5. Target Limit State Probability

The limit state probability is a quantitative measure of structural performance. In relation to public safety there are two distinct areas in which probabilitic risk assessment can be applied ; the first of these necessitates mainly the probabilistic assessment of containment structures, in order to establish the probability that the specific conditions under which these inherent feature are operational, would be maintained in service. In second area, a combination of sensitivity analysis and probabilistics assessment can be used to determine the likelihood that, within the specific conditions where inherent safety is claimed, there would be no unsafe departure from the postulated behavior in all conceivable transients. Inherently safe containment structure have some prospects of proving reasonably competitive with more conventional design because they have a minimal requirement for active safety grade systems. Consequently, the reliability required for virtually all the systems, is dictated by economic, rather than safety considerations. Thus target limit state probability, in the form of reliability analysis, can be used effectively to optimize these active systems to meet investment risk targets. In some inherently safe containment structures, it is claimed that safety is entirely independent of the structural integrity of containment intervals. Consequently, Target limit state probability can be of value in the optimization of the structural aspects of the containment to meet a specified investment risk target.

This study, the main emphasis is on the use of target limit state probability to determine factors which are likely contributiors to the quantitative safety objectives that would be adopted by a country embarking on a large program of nuclear power plants structures with a high degree of inherent safety, and the factors which would determine the way in which the overall goal would be allocated between the major safety fuctions.

The selection of a target limit state probability should be consider many factors : the characteris-characteristics of the limit states, the consequence of failure, and the risk evaluation and damage cost.

It is anticipated that the target limit state probability will be set by the regulatory authority

Table 2. Serviceability Limit State Probability (D+L+P) (/yr)

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}

or the code committee. However, in this study determine the target limit state probability is assumed to be one of the 3 values refer to consult the paper [17] : 2.5×10^{-8}, 1.0×10^{-8} and 2.5×10^{-9} per year.

6. Probability-Based Load Factors

The load factors are calibrated by using an iterative heuristic optimization technique, selecting a set of load factors that minimize the function with a set of fixed resistance factor. The minimum value of the objective function occurs when load factor is optimal. Various loads act on a reinforced concrete containment structure. The loads involve randomness and uncertainties. The parameters for the accidental pressure load are assumed to be in the reference (12).

The structural designs for the earthquake loads and the seismic hazard assessment in Korea have been reported. [12-15] Based on the available data for Korea, the earthquake parameters for nuclear power plants are assumed to be in reference (12).

The dead load factor γ_D is preset to be 1.2 or 0.9 as in the A58 Standard.[16]

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 2. The optimum objective function values and corresponding load factors are computed in Table 4.

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.[16] The limit state probabilities were computed as shown in Table 3. The optimum objective function values and corresponding load factors are computed in Table 5.

Table 3 Serviceability Limit State Probability (D+L+E) (/yr)

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}

Table 4 Optimum Object Function Values and Proposed Design Accidental Load Factors

Target limit state	Accidental load		
probability (/yr)	Optimum $I(\gamma_P)$	γ_P	Proposed
2.5×10^{-8}	2.045	1.288	1.3
1.0×10^{-8}	3.163	1.328	1.3
2.5×10^{-9}	4.360	1.380	1.4

Table 5 Optimum Object Function Values and Proposed Design Earthquake Load Factors

Target limit state	Earthquake load		
probability (/yr)	Optimum$I(\gamma_{ES})$	γ_{ES}	Proposed
2.5×10^{-8}	10.579	1.533	1.5
1.0×10^{-8}	11.631	1.597	1.6
2.5×10^{-9}	13.394	1.721	1.7

7. Proposed Design Load Factors

The design load factors specified in the ASME code [18] are $\gamma_p = 1.5$ (abnormal environment) and $\gamma_{ES} = 1.0$ (extreme environment). It can be seen from Table 4 that optimum values of the objective function are I $(\gamma_p) = 2.045$ and the corresponding load factors are $\gamma_p = 1.288$ for $P_{fo} = 2.5 \times 10^{-8}$per year.

It can be seen from Table 5 that optimum values of the objective function are I $(\gamma_{ES}) = 10.579$ and the corresponding load factors are $\gamma_{ES} = 1.533$ for $P_{fo} = 2.5\text{x}10^{-8}$ per year.

The design load factors proposed herein for design of the reinforced concrete containment structures are shown in Table 4 and Table 5. Note that these load factors are different from those in the ASME code.

8. Reliability Assessments for Containment Structures

Reliability assessments of the containment structures shown, Table 6 and Table 7, are carried out using the probabilistic descriptions of load and material for $P_{fo} = 1.0 \times 10^{-8}$ per year. The limit state probabilities for design of two sample reinforced concrete containment structures using the ASME code are shown in Table 6. It can be seen from Table 6 that total limit state probabilities for the two sample containments designed according to the ASME code are quite different.

Table 6. Containment Structures Designed by ASME Code

Design Criteria	Load combination	Limit State Probability CASE Ⅲ, Sample Ⅲ	Limit State Probability Case Ⅲ, Sample Ⅳ
ASME Code	$D+L+1.5P_a$	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}

Table 7. Containment Structures Designed by this Study

Design Criteria	Load combination	Limit State Probability CASE Ⅲ, Sample Ⅲ	Limit State Probability Case Ⅲ, Sample Ⅳ
This Study	$0.9D+L+.3P_a$	3.538×10^{-7}	3.483×10^{-7}
	$1.2D+L+1.5E_{ss}$	5.240×10^{-7}	3.870×10^{-9}
	Total	8.778×10^{-7}	3.486×10^{-7}

The limit state probabilities for design of two sample reinforced concrete containment structures using the proposed load factors are shown Table 7. It can be seen from Table 7 that 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 consistent safety levels than the ASME code.

9. 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 serviceability limit state design of reinforced concrete containment structures are proposed. And 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.

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