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한국전산구조공학회 학술발표회 논문집

原子力 遮蔽 構造物의 設計荷重 組合 規準

LOAD COMBINATION CRITERIA FOR DESIGN OF NPP COINTAINMENT STRUCTURES

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ABSTRACT

The current load combination criteria for design of nuclear power plant structures are not based on the probability-based design concept but rely on the conventional design concept. In this paper, a load combination criteria for design of NPP cointainment structures are proposed based on a FEM-based random vibration analysis. More accurate reliability analyses under various dynamic loads such as earthquake loads were made possible by incorporating the FEM and random vibration theory, which is different from the conventional reliability analysis method. In this paper, the load factors for the design of NPP structures in Korea are proposed by considering appropriate load combination criteria for design.

1. INTRODUCTION

The safety of nuclear power plant structures should be secured against all kinds of loading due to various natural disasters or extraordinary accidental loads. Nuclear power plants were constructed so far and a number of units are under design or planning stage. However, the current design criteria and the design loads for nuclear power plants are not probability-based. 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 NPP structures, and to show how recently developed stochastic and advanced structural reliability methods [1,2,3] 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 design of nuclear power plant structures in Korea.

2. PROBABILISTIC MODEL FOR LOAD AND RESISTANCE

2.1 Loads

A concrete NPP 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 [4]. 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 $S_g(\omega)$ [5,6] :

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

where S_0 is a random variable which represents the power spectral 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 of the given site. The earthquake parameters for the nuclear power plants in Korea are summarized in Table 1.

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Table 1 Parameters of Earthquake Model

Items	sample I	sample II	sample III	sample IV
$a_{SSE}(g)$	0.20	0.25	0.28	0.32
ω_g	8π	5π	8π	8π
μ_e(sec)	10	10	10	20
λ_E	0.0147	0.0263	0.0353	0.0499

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
$\lambda_p(/yr)$	1.0×10^{-5}	1.0×10^{-4}	1.0×10^{-5}
μ_{dp}(sec)	600	1200	1200
Mean/Design	0.9	0.83	0.88
C.O.V.	0.12	0.16	0.20

2.2 Resistance

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 (kg/cm^2)	C.O.V.	Remark
Concrete	420	0.14	91 days
Re-Bar	4990	0.11	ASTM Grade 60

3. LIMIT STATE CONDITION

For the calibration of load criteria for the design of NPP structures a ultimate strength limit state of flexural is considered. The limit state is considered to have reach the limit state if the crushing strength of the concrete is reached at the extreme fiber of the wall cross-section and/or if the reinforcement steels begin to yield. The limit state condition can be expressed as follows.

$$\sigma_c - 0.85\sigma_c' \geq 0 \quad , \quad \sigma_s - \sigma_y \geq 0. \tag{2}$$

where σ_c is the compressive concrete stress at the extreme fibers and σ_s is the stress in the reinforcement steels.

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. The limit state surface consists of the segments of following eight straight lines which define the octagonal area shown in Fig. 1.

$$g_j\{\tau\} = R_j - \{C_j\}^T \cdot \{\tau^{(e)}\} = 0 \quad (j = 1, 2, ..8). \tag{3}$$

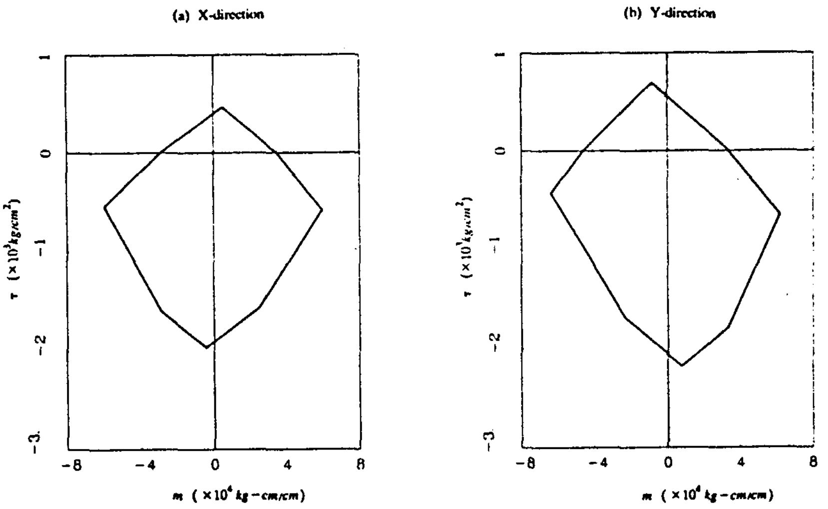

Fig.1 Limit State Surface

4. LIMIT STATE PROBABILITY

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.

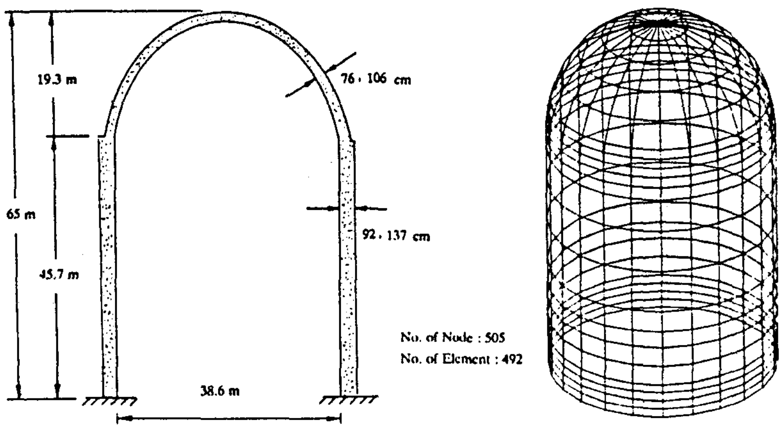

Fig.2 Three-Dimensional Finite Element Model

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.

$$\begin{aligned} &D+L+P \\ &D+L+E \qquad (4) \\ &D+L+P+E \end{aligned}$$

where D = dead load, L = live load, P = accidental

The limit state probability can be written as

$$P_f = P_{f_{(D/L)}} + P_{f_{(D/L+P)}} + P_{f_{(D/L+E)}} + P_{f_{(D/L+P+E)}} \qquad (5)$$

$$P_{f_{(c)}} = \lambda_{(c)} T P_{f/(c)} \qquad (6)$$

where $\lambda_{(c)}$ is the rate of occurrence of the load combination (c), $P_{f/(c)}$ is the conditional limit state probability. The limit state probability of the NPP structures as a whole and the limit state probabilities under various load

Table 4 Strength Limit State Probability (40 yr)

Load Combination	Critical Height	Direction	Limit State Probability
D + L			0
D + L + P1	11.5 m	X	2.233×10^{-4}
D + L + P2	*	X	2.338×10^{-24}
D + L + E	Bottom	Y	1.024×10^{-4}
D + L + P1 + E	11.5 m	X	8.494×10^{-11}
D + L + P2 + E	Bottom	Y	2.821×10^{-10}
Total			3.257×10^{-4}

* $P_1 = 1.05 kg/cm^2$, $P_2 = 3.16 kg/cm^2$

It can be observed from Table 4 that the limit state probability due to a coincidence of earthquake and 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 NPP containment structures for this rare event.

5. LOAD FACTORS AND LOAD COMBINATION CRITERIA

The load factors are calibrated by using optimization technique, selecting a set of γ_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.

$$I(\gamma_i) = \sum_{i=1}^{n} \omega_i (\log P_{f_i} - \log P_{f_o})^2 \tag{7}$$

in which P_{f_i} is the limit state probability for the i-th sample containment, P_{f_o} 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 1.2 or 0.9 as in the A58 Standard [7]. Target limit state probability is assumed to be one of the 3 values: 1×10^{-5}, 1×10^{-6}, 1×10^{-7} for a design lifetime of 40 years.

For the case of (D+L+P) load combination, the live load factor of zero, because the live load has a stabilized effect. The limit state probabilities during lifetime were computed as shown in Table 5, and the corresponding objective functions are plotted in Fig. 3. The objective function I is computed at several values of γ_p and these values are shown in Fig. 3. It can be seen from Fig. 3 that minimum value of objective function results in near $\gamma_P = 1.2$ for $P_{f_o} = 1 \times 10^{-6}$.

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 [7]. The limit state probabilities were computed as shown in Table 6, and the the objective function vs. γ_{ES} are shown in Fig. 3. It can be seen from Fig. 4 that minimum value of objective function results in near $\gamma_{ES} = 1.5$ for $P_{f_o} = 1 \times 10^{-6}$.

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

$$\begin{aligned} &0.9D + 1.2P_a \\ &1.2D + L + 1.5E_{ss} \\ &0.9D - 1.5E_{ss} \end{aligned} \tag{8}$$

This load combinations are different from those in ASME code or in the reference [3].

Table 5 Strength Limit State Probability ($0.9D + \gamma_P P_a$)

γ_P	Case I	Case II	Case III
1.0	0.2565×10^{-4}	0.5768×10^{-4}	0.8700×10^{-4}
1.1	0.2646×10^{-5}	0.1447×10^{-4}	0.3445×10^{-4}
1.2	0.9297×10^{-7}	0.2356×10^{-5}	0.1044×10^{-4}
1.3	0.1641×10^{-8}	0.2389×10^{-6}	0.2428×10^{-5}
1.4	0.7584×10^{-11}	0.1266×10^{-7}	0.3606×10^{-6}
1.5	0.2425×10^{-13}	0.4183×10^{-9}	0.5527×10^{-7}
1.6	0.2113×10^{-16}	0.6581×10^{-11}	0.4179×10^{-8}

Table 6 Strength Limit State Probability ($1.2D + L + \gamma_{ES} E_{ss}$)

γ_{ES}	Sample I	Sample II	Sample III	Sample IV
1.0	8.978×10^{-5}	7.735×10^{-5}	3.746×10^{-3}	1.459×10^{-3}
1.1	2.925×10^{-5}	2.034×10^{-5}	2.631×10^{-3}	7.328×10^{-4}
1.2	8.420×10^{-6}	4.680×10^{-6}	1.674×10^{-3}	3.193×10^{-4}
1.3	2.152×10^{-6}	9.394×10^{-6}	9.526×10^{-4}	1.232×10^{-4}
1.4	4.884×10^{-7}	1.664×10^{-7}	4.852×10^{-4}	4.317×10^{-5}
1.5	1.004×10^{-4}	2.585×10^{-7}	2.257×10^{-4}	1.401×10^{-5}
1.6	1.788×10^{-8}	3.575×10^{-8}	9.733×10^{-5}	4.171×10^{-6}
1.7	2.866×10^{-9}	4.161×10^{-9}	3.896×10^{-5}	1.145×10^{-6}
1.8	4.210×10^{-10}	4.390×10^{-10}	1.465×10^{-5}	2.899×10^{-7}

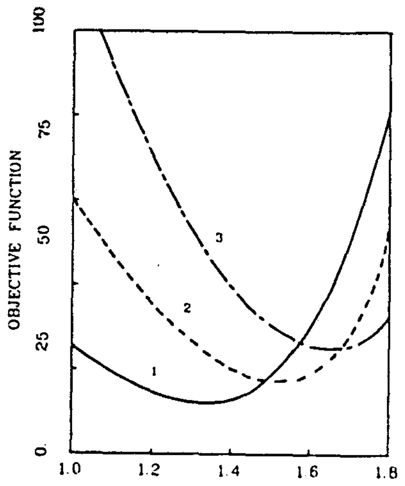

Fig. 3 Load Factor γ_P

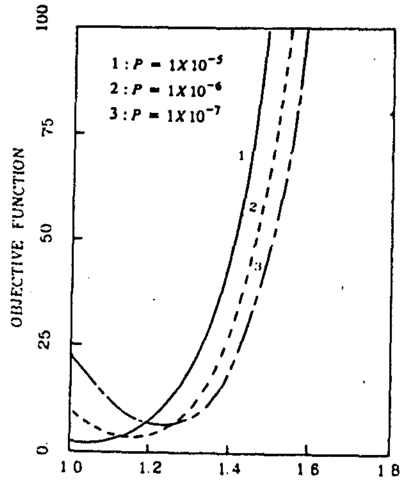

Fig. 4 Load Factor γ_{ES}

6. *DISCUSSION AND CONCLUSION*

In this paper, the use of the ultimate strength limit state is suggested as a critical failure criteria of concrete NPP containment. This paper presented a practical probability-based load combination criteria for designing NPP containment structures.

Load factors are selected on the basis of strength limit state and target limit state probability. The load factor for accidental pressure $\gamma_P = 1.2$ and the load factor for SSE $\gamma_{ES} = 1.5$ for $P = 1 \times 10^{-6}$ are appropriate for concrete nuclear containment structures in Korea.

The proposed load factors were proved to be in accordance with a set of code performance objective and showed consistency in the limit state probability. The proposed load combination criteria are calibrated based on the available statistical data pertaining to loads and resistance. Accordingly, when the statistical data bases are updated or improved, the reliability analysis method shown in this paper can be readily utilized to update the load factors resulting from these changes.

The proposed load combination criteria for design of concrete cointainment structures may possibly substitute the ASME code provisions which are currently used in Korea.

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