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Probability Based Load Combinations for Design of Category I Structures

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Abstract

This paper discusses a reliability analysis method and a procedure for developing the load combination design criteria for category I structures. For safety evaluation of category I concrete structures under various static and dynamic loads, a probability-based reliability analysis method has been developed. This reliability analysis method is also used as a tool for determining the load factors for design of category I structures. In this paper, the load combinations for design of concrete containments, corresponding to a target limit state probability of 1.0 x 10^{-6} in 40 years, are described. A comparison of containments designed using the ASME code and the proposed design criteria is also presented.

1. Introduction

The safety of nuclear power plant structures is of primary concern to regulatory agencies, the nuclear industry, and the general public because of the serious socioeconomic consequences that could result from structural failures. To ensure the structural safety, nuclear structures must be designed to withstand all kinds of loads and load combinations that could occur during their lifetime. It is recognized that the loads involve random and other uncertainties in nature. Similarly, the structural resistance cannot be precisely determined without uncertainties. In view of the randomness and uncertainties, a probabilistic approach for the development of load combination design criteria is a rational choice. In order to develop such probability-based design criteria, a reliability analysis method applicable to nuclear structures is needed. This paper discusses the reliability analysis method developed at the Brookhaven National Laboratory (BNL) and the procedure for establishing load combination design criteria for category I structures, specifically, reinforced concrete containment structures.

2. Reliability Analysis Method for Concrete Containment Structures

For the safety evaluation of category I concrete structures under various static and dynamic loads, a probability-based reliability analysis method has been developed.[1] An important feature of this method is that finite element analysis and random vibration theory have been incorporated into the reliability analysis. In the method, an appropriate probabilistic model is established for each load. For example, accidental pressure is idealized as a rectangular pulse with random intensity and duration and is assumed to occur according to the Poisson arrival law. Earthquake ground acceleration is represented by a segment of a stationary Gaussian process with a zero mean and Kanai-Tajimi spectrum. Furthermore, all possible seismic hazards at a site, which is represented by a hazard curve, are also included in the analysis. The limit state of the structure is then analytically defined and the corresponding limit state surface is established.

For static loads, the SAPV computer program is used to evaluate the elemental stress resultants. For the dynamic load, which is characterized as a stationary vector process with a specified cross-spectrum density matrix, the SAPV finite element program is only used to evaluate the dynamic characteristics of the structure such as natural frequencies and modes. Using these characteristics and random vibration theory, the structural response is obtained in the form of a cross-spectral density matrix, which upon integration produces a response second moment (cross-correlation) matrix. Under the assumption that the loads and structural responses are Gaussian, techniques for estimating the rate at which a response vector outcrosses the limit state surface have been developed. This outcrossing rate can, in turn, be used to evaluate the limit state probabilities of the structure subjected to dynamic loads. The reliability analysis methods for dynamic and static loads are then combined. Using this method, it is possible to assess the reliability of a containment under various static and dynamic loads.

Currently, the reliability analysis method for concrete containments subjected to dead load, live load, accidental pressure, tornado, SRV load and ground earthquake acceleration has been established. This reliability analysis method has also been applied to selected existing containment structures in order to assess their safety margins under various load combinations. The details of these reliability assessments are described in Refs. 1 and 2.

3. Procedure for Developing Probability-Based Load Combination Design Criteria

In principle, the reliability analysis method described above could be utilized directly in structural design. However, the probabilistic method requires expert judgement on the probabilistic models of loads and resistance, and on the target limit state probability etc., thus, it is not suitable for the routine design of nuclear structures.[3] Load combination criteria, which are in a deterministic format and yet reflect the probabilistic nature of the design parameters, are more appropriate for routine design purposes. The procedure for developing probability-based load combination criteria for the design of containments and other category I structures is as follows:

1. Select an appropriate load combination format. (e.g., LRFD format)
2. Establish representative structures.
3. Define limit states and select a target limit state probability.
4. Assign initial values for all parameters (load factors etc.) associated with the selected load combination format.
5. Design each representative structure.
6. Determine the limit state probability of each representative structure.
7. Compute the objective function measuring the difference between the target limit state probability and the computed limit state probability.
8. Determine a new set of parameters (load factors) along the direction of maximum descent with respect to the objective function.
9. Repeat steps 5 to 8 until a set of parameters that minimize the objective function is found.

The procedure has been utilized in determining load factors for concrete containments as described in Ref. 4.

4. Proposed Load Combination Criteria

For a target limit state probability, $P_{f,T}$ of 1.0×10^{-6} per 40 years, load combinations for designing PWR concrete containments are[4]:

$$\left.\begin{array}{l} 1.2\,D + 1.6\,L + T_o + R_o \\ 0.9\,D + 1.2\,P_a + T_a + R_a \\ 1.2\,D + L + 1.7\,E_{ss} + T_o + R_o \\ 0.9\,D - 1.7\,E_{ss} \end{array}\right\} \leqslant \phi_i\,R_i \tag{1}$$

It is clear that the use of such criteria would entail no major change in the way that routine structural design calculations are performed. However, in contrast to existing design procedures, the proposed criteria are risk-consistent and have a well-established rationale.

The major features of the proposed load combinations can be summarized as follows:

1. The load combinations are in a Load and Resistance Factor Design (LRFD) format using the principal load-companion loads concept.
2. Load factors and resistance factors are, in general, selected on the basis of limit states and a target limit state probability.
3. The load factor for accidental pressure is equal to 1.2. This new load factor is smaller than the current value, which is 1.5.
4. One design earthquake, i.e., SSE, is selected to represent seismic hazards. This is in contrast to current practice, where two kinds of design earthquakes, i.e., SSE and OBE are employed. The load factor for SSE is determined to be 1.7.
5. The load combination involving both accidental pressure and SSE, i.e., abnormal/extreme environmental conditions in the current ASME code, is not recommended for inclusion in the proposed design criteria.

For more details pertaining to the proposed load combination criteria, the reader is referred to Ref. 4.

5. Comparison of Containments Designed Using ASME Code and Proposed Criteria

For this comparative study, containments subjected to dead load, accidental pressure and earthquakes during a service life of 40 years were utilized. The design of two representative concrete containments (Samples 1 and 3 in Table I) were carried out using the current ASME code and the proposed design criteria.[4] As shown in Table I, the design parameters for concrete containment are predetermined except for the reinforcements. The minimum required rebar area in the most critical elements and the governing load combinations are shown in Table II. It can be seen from this table that the proposed criteria result in less reinforcement except in one case.

Reliability analyses of these containments are carried out by the method developed by BNL. The results of the reliability assessments of the containment structures designed by the ASME code and the proposed code are shown in Tables III and IV, respectively. As can be seen from these tables, the overall limit state probabilities for the two containments designed by the ASME code are quite different: 3.18×10^{-5} vs 8.25×10^{-14} (Table III), while the overall limit state probabilities for the containments designed by the proposed criteria are much closer to each other: 2.19×10^{-6} vs. 6.95×10^{-7} (Table IV). These results are expected because the load factors in the proposed load combination criteria are obtained from an optimizing process aimed at achieving consistent reliability for all design conditions.

6. Concluding Remarks

This paper discusses reliability analyses and load combination design criteria for category I structures. For the safety evaluation of category I concrete structures under various static and dynamic loads, a probability-based reliability analysis method has been developed. An important feature of this method is that finite element analysis and random vibration theory have been incorporated into the reliability analysis. In the method, an appropriate probabilistic model is established for each load. The limit state of the structure is analytically defined and the corresponding limit state surface is established. Finally, limit state probabilities for various load combinations are evaluated.

A procedure for developing probability-based load combination criteria for design of category I structures has also been established. In this procedure, the proposed load combinations is in load and resistance factor design (LRFD) format which uses the principal load-companion load concept. The load and resistance factors are, in general, determined on the basis of limit states and target limit state probabilities. This procedure has been utilized in determining load factors for design of concrete containments.

7. References

/1/ Shinozuka, M., Hwang, H. and Reich, M., "Reliability Assessment of Reinforced Concrete Containment Structures", Nuclear Engineering and Design 80 (1984) 247-267.

/2/ Hwang, H., Shinozuka, M., Kawakami, J. and Reich, M., "Reliability Assessment of Indian Point Unit 3 Containment Structures Under Combined Loads", in Structural Engineering in Nuclear Facilities, Vol. 1, ed. J.J. Ucciferro, ASCE (1984) 274-293.

/3/ Ellingwood, B., Probability Based Safety Checking of Nuclear Plant Structures, NUREG/CR-3628, BNL-NUREG-51737, (December 1983).

/4/ Hwang, H., et al., Probability Based Load Combination Criteria for Design of Concrete Containment Structures, BNL-NUREG-51795, NUREG/CR-3876, (March 1985).

NOTICE

This work was performed under the auspices of the U.S. Nuclear Regulatory Commission, Washington, D.C. The views expressed in this paper are those of the authors. The technical contents of this paper have neither been approved nor disapproved by the United States Nuclear Regulatory Commission and Brookhaven National Laboratory.

Table I. Representative PWR Reinforced Concrete Containments.

Design Parameters	Sample 1	Sample 2	Sample 3	Sample 4
inside radius	70'-0"	60'-0"	60'-0"	70'-0"
dome rise ratio	1.0	1.0	1.0	1.0
cylindrical height	150'-0"	150'-0"	150'-0"	150'-0"
cylindrical wall thickness	4'-6"	3'-6"	4'-6"	3'-6"
dome wall thickness	3'-6"	2'-6"	3'-6"	2'-6"
concrete compressive strength (psi)	4000	4000	5000	5000
steel yield strength (psi)	60,000	60,000	60,000	60,000
dead load (lb/ft^3)	150	150	150	150
accidental pressure (psi)	47	42	52	57
SSE (g)	0.17	0.32	0.50	0.25
soil	Rock	Deep Cohesionless	Rock	Deep Cohesionless
earthquake duration (sec)	10	20	20	10

H. Hwang

m. 1 2/2

Table II. Comparison of Required Rebar Area.

Sample	Direction	$A_s(in^2/in)$	
		ASME Code	Proposed Code
1	X	0.577 $(1.0\ D + 1.5\ P_a)$	0.493 $(0.9\ D + 1.2\ P_a)$
	Y	0.566 $(1.0\ D + 1.25\ P_a + 1.25\ E_o)$	0.341 $(0.9\ D + 1.2\ P_a)$
3	X	0.557 $(1.0\ D + 1.5\ P_a)$	0.427 $(0.9\ D + 1.2\ P_a)$
	Y	0.985 $(1.0\ D + 1.0\ P_a + 1.0\ E_{SS})$	1.068 $(0.9\ D - 1.7\ E_{SS})$

NOTE: Symmetry of the rebar arrangement is assumed and A_s shown in the Table is one-half of the total rebar area.

H. Hwang [illegible]

Table III. Reliability Assessments of Containments Designed by ASME Code.

Sample	Load Combination	Unconditional Limit State Probability	Critical Elements
1	$D + P_a$	7.14 -14	97,...120
	$D + E$	1.11 -14	6,7,18,19
	$D + P_a + E$	7.70 -17	6,7,18,19
	Overall	8.25 -14	
3	$D + P_a$	3.14 -14	97,...120
	$D + E$	3.18 -5	6,7,18,19
	$D + P_a + E$	2.77 -12	6,7,18,19
	Overall	3.18 -5	

H. Hwang

Table IV. Reliability Assessments of Containments Designed by Proposed Criteria.

Sample	Load Combination	Unconditional Limit State Probability	Critical Elements
1	D + P_a	6.63 -7	97,...120
	D + E	3.23 -8	6,7,18,19
	D + P_a + E	8.34 -11	6,7,18,19
	Overall	6.95 -7	
3	D + P_a	2.29 -8	97,...120
	D + E	2.17 -6	6,7,18,19
	D + P_a + E	3.41 -13	6,7,18,19
	Overall	2.19 -6	