Probability Based Load Factors for Design of Concrete Containment Structures

H. Hwang, S. Kagami, M. Reich
Brookhaven National Laboratory, Dept. of Nuclear Energy, Upton, New York 11973, U.S.A.
B. Ellingwood
National Bureau of Standards, Center for Building Technology, Washington, D.C. 20234, U.S.A.
M. Shinozuka
Columbia University, Dept. of Civil Engineering and Engineering Mechanics, New York, N.Y. 10027, U.S.A.

Abstract

This paper describes a procedure for developing probability-based load combinations for the design of concrete containments. The proposed criteria are in a load and resistance factor design (LRFD) format. The load factors and resistance factors are derived for use in limit states design and are based on a target limit state probability. In this paper, the load factors for accident pressure and safe shutdown earthquake are derived for three target limit state probabilities. Other load factors are recommended on the basis of prior experience with probability-based design criteria for ordinary building construction.

1. Introduction

In the design of nuclear power plant structures, both extreme and abnormal loading conditions must be considered. This requirement results in a large number of load combinations in the design criteria. Furthermore, the load factors and the allowable stresses specified in the code are determined by the code committee primarily on the basis of collective judgement and experience. Hence, a rational procedure is needed to justify the number of load combinations and to determine appropriate load factors. This paper describes the development of probability-based load combination criteria for the design of concrete containment structures.

2. Procedure For Establishing Load Combination Criteria

The procedure for developing probability-based load combination criteria for the design of containments is as follows[1,2]:

1. Select an appropriate load combination format.
2. Establish representative structures.
3. Define a limit state 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. Evaluate an objective function which measures 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.

3. Load Factors For Accidental Pressure and Safe Shutdown Earthquake

The above procedure will be illustrated for containment structures subjected only to dead load, accidental pressure and earthquake during their lifetimes. The derivation of load factors for these loads are described in this section.

3.1 Load Combination Format

The load and resistance factor design (LRFD) format has been selected for this study. The LRFD format is simple enough to be used in routine design while offering sufficient flexibility to achieve consistent reliabilities in various design situations.

If three loads, i.e., dead load, earthquake and accidental pressure are considered, the load combinations in the LRFD format are expressed as follows:

$$
\begin{aligned}
&0.9D + \gamma_p P_a \leqslant \phi_i R_i \qquad (1)\\
&1.2D + \gamma_{ES} E_{ss} \leqslant \phi_i R_i\\
&0.9D - \gamma_{ES} E_{ss} \leqslant \phi_i R_i
\end{aligned}
$$

where D, P_a, E_{ss} are the load effect due to design dead load, design pressure and Safe Shutdown Earthquake (SSE), respectively. Load factors γ_p and γ_{ES} are for accidental pressure and SSE. ϕ_i and R_i are resistance factor and nominal structural resistance for the i-th limit state under consideration. The dead load factor and resistance factors are preset to simplify the optimization. A dead load factor of 1.2 (or 0.9 when the dead load has a stablizing effect) has been found to be adequate to account for uncertainty in dead load[2]. Proposed resistance factors for concrete design that are consistent with A58 load requirements have been derived[3], and are used in this study.

3.2 Selection of Representative Containment Structures

An important requirement for codified structural design is that all the structures designed according to a code should meet the code performance objectives. In order to test if this requirement is satisfied, a set of representative (sample) structures must be selected for evaluating the code. In this study, by examining the inventory of PWR reinforced concrete containments in the United States, four representative PWR containments are determined, as described in the following[1]:

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

Design Parameters	Sample 1	Sample 2	Sample 3	Sample 4
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
safe shutdown earthquake (g)	0.17	0.32	0.50	0.25
soil	Rock	Deep Cohesionless	Rock	Deep Cohesionless
earthquake duration (sec)	10	20	20	10

3.3 Limit State

A limit state represents a state of undesirable structural behavior. In this study, the limit state for containments is described as follows: at any time during the service life of the structure, the structure is considered to have reached the limit state if a maximum concrete compressive strain at the extreme fiber of any cross-section is equal to 0.003, while the yielding of rebars is permitted.

3.4 Design of Containment Structures

Each sample containment is assumed to be fixed at the base and has to be designed according to the proposed load combinations with trial load and resistance factors, design loads and nominal resistance. For design loads and nominal resistance, the current values specified in codes are generally used.

For structural analysis of containments, three-dimensional finite element models are used. The finite element utilized in the analysis is the shell element as described in the SAP V computer code. The element stress resultants for dead load and accidental pressure are obtained from static analysis. For seismic analysis, the response spectrum analysis method is employed. The horizontal and vertical response spectra used in this study are those specified in the Regulatory Guide 1.60. The damping ratio is taken to be 7 percent of criterial for SSE as specified in the Regulatory Guide 1.61. The square root of the sum of squares (SRSS) method is used to combine the responses in three directions. Using principles of ultimate strength design for reinforced concrete, the minimum required rebar area is determined.

3.5 Probabilistic Representations for Loads and Material Strength

Since the loads and structural resistance intrinsically involve random and other uncertainties, an appropriate probabilistic model for them must be established in order to perform reliability analysis.

Dead Load

The dead load arises primarily from the weight of the containment wall. There is some uncertainty as to the actual magnitude of the dead load[2]. However, the large variabilities in earthquake and accidental pressure tend to overshadow the variability in dead load. As a result its effect on the limit state probabilities is minor. Thus, for the purpose of this analysis, dead load is assumed to be deterministic and is equal to the design value.

Accidental Pressure

The accidental pressure is considered to be a quasi-static load that is uniformly distributed on the containment wall. The accidental pressure is idealized as a rectangular pulse that occurs in accordance with the Poisson law during the containment life. Under these assumptions, three parameters are required to model the accidental pressure: the mean occurrence rate, the mean duration, and the intensity P. Intensity P is considered as a random variable. In this study, the mean occurrence rate and the mean duration are taken to be 1.68×10^{-3} per year and 1200 sec, respectively. The intensity is assumed to be normally distributed with a mean value of 0.9 times the design pressure P_a and a coefficient of variation of 0.12[1].

Earthquake

The seismic hazard at a site of a nuclear power plant is described by a seismic hazard curve. In this study, the probability distribution $F_A(a)$ of the annual peak ground acceleration A is assumed to be the Type II extreme value distribution[4],

$$F_A(a) = \exp\left[- (a/u)^{-\alpha} \right] \tag{2}$$

where α and μ are two parameters to be determined. The average value of α for the U.S. is estimated to be 2.7[1]. The parameter μ is computed based on this α value and the assumption that the annual probability of exceeding the safe shutdown earthquake at a site is 4×10^{-4} per year. The lower and upper bounds of peak ground acceleration are required in the analysis. The lower bound, a_o, indicates the minimum peak ground acceleration for any ground shaking to be considered as an earthquake. a_o is assumed to be 0.05 g. The upper bound, a_{max}, represents the largest earthquake possible at a site. In this paper, a_{max} is chosen to be $2a_{SSE}$.

For reliability analysis, the earthquake ground acceleration is assumed to act only in the global x direction. The earthquake ground acceleration, on the condition that an earthquake occurs, is idealized as a segment of a zero-mean stationary Gaussian process, described in the frequency domain by a Kanai-Tajimi power spectral density.

$$S_{gx}(\omega) = S_o \frac{1 + 4\zeta_g^2 (\omega/\omega_g)^2}{[1 - (\omega/\omega_g)^2]^2 + 4\zeta_g^2 (\omega/\omega_g)^2} \tag{3}$$

where the parameter S_o is a random variable which represents the intensity of an earthquake. The distribution of S_o can be determined as shown in Ref. 5. Parameters ω_g and ζ_g are the dominant ground frequency and the critical damping, respectively, which depend on the site soil conditions. For rock and deep cohesionless soil conditions, ω_g, is taken to be 8π rad/sec and 5π rad/sec, respectively. ζ_g is taken to be 0.6 for both soil conditions[4]. The mean duration of the stationary phase of the earthquake acceleration is assumed to be 10 or 20 seconds in this study.

Material Strength

The geometry of the containments is assumed to be deterministic while material strengths are random variables. The concrete compressive strength, f'_c, is normally distributed with coefficient of variation (CoV) of 0.14 and a mean value at 1 year, $\overline{f'}_c = 1219 + 1.02\, f'_{cn}$ (psi), in which f'_{cn} = specified compressive strength of concrete[6]. The yield strength f_y of ASTM A 615 Grade 60 reinforcement is assumed to have lognormal distribution with a mean value of 71.0 ksi and CoV of 0.11[6].

3.6 Reliability Assessment

A reliability analysis method has been developed[5] for reliability assessments of these containments. By utilizing this method, limit state probabilities for a reference period of 40 years can be determined for structures under various static and dynamic loads. The methodology can also evaluate the coincidence probabilities of various load combinations. This is important since it is on the basis of the coincidence probabilities that a decision may be made on whether or not a particular load combination (among all the possible mutually exclusive load combinations) is to be considered for design.

3.7 Determination of Load Factors

If a target limit state probability $P_{f,T}$ is specified, the load and resistance factors can be determined such that the limit state probabilities of the sample containments are sufficiently close to the target limit state probability. The closeness is measured by an objective function, defined as follows:

$$\Omega(\gamma_p, \gamma_{ES}) = \sum_{i=1}^{4} (\log P_{f,i} - \log P_{f,T})^2 \tag{4}$$

where $P_{f,i}$ is the limit state probability computed for the i-th sample containment and $P_{f,T}$ is the specified target limit state probability for 40 years. The optimum load factors γ_{ES} and γ_p may be obtained using a minimization technique. The optimum load factors for three target limit state probabilities are determined as follows[1]:

Target limit state probability $P_{f,T}$	Optimum load factors γ_{ES}	γ_p
1.0×10^{-5}	1.6	1.1
1.0×10^{-6}	1.7	1.2
1.0×10^{-7}	2.0	1.2

4. Other Load Factors

Tentative load factors for prestress force, equipment and live loads, temperature effects, and pipe reactions appearing in the load combinations for designing containments are presented in Ref. 1. These factors were not determined through the optimization process described previously for P_a and SSE, but rather on the basis of prior experience with probability-based design for ordinary building construction[2]. However, the load factors are consistent with the levels of uncertainty in the loads.

5. Summary and Recommendations

This paper has presented a methodology for developing practical load combination criteria for designing concrete containments. These load combinations are consistent with a set of code performance objectives expressed in terms of target limit state probabilities. Using the LRFD format, load factors consistent with three target limit state probabilities were derived for load combinations involving earthquake and accidental pressure resulting from a design basis accident. These loads were emphasized because they are significant for practically all containments constructed in the United States. Experience with the development of probability-based design criteria for building construction has made it possible to preassign numerical values for many of the other load and resistance factors appearing in the checking equations, thus keeping the optimization of the design criteria manageable.

Tentative design load combinations corresponding to a target limit state probability of 1.0×10^{-6} and $a_{max} = 2a_{SSE}$ for PWR containments are:

$$\left.\begin{array}{l} 1.2\,D + 1.6\,L + T_o + R_o \\ 0.9\,D + 1.2\,P_a + T_a + R_a \\ 1.2\,D + L + 1.7\,E_{ss} + T_o + R_o \\ 0.9\,D - 1.7\,E_{ss} \end{array}\right\} \leqslant \phi_i R_i \qquad (5)$$

The load combination involving both accidental pressure and SSE is not recommended for inclusion in the proposed design criteria. 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.

6. References

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NOTICE

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