Reliability Assessment of Nuclear Structural Systems

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Reliability assessment of nuclear structural systems have been receiving more emphasis over the last few years. This paper deals with the recent progress made by the Structural Analysis Division of Brookhaven National Laboratory (BNL), in the development of a probability-based reliability analysis methodology for safety evaluation of reactor containments and other seismic category I structures. An important feature of this methodology is the incorporation of finite element analysis and random vibration theory. By utilizing this method, it is possible to evaluate the safety of nuclear structures under various static and dynamic loads in terms of limit state probability. Progress in other related areas, such as the establishment of probabilistic characteristics for various loads and structural resistance, are also described. Results of an application of the methodology to a realistic reinforced concrete containment subjected to dead and live loads, accidental internal pressures and earthquake ground accelerations are presented.
1. Introduction

Structures for nuclear power plant facilities must be designed to safely and effectively withstand all kinds of loads and load combinations that may be expected to occur during their lifetime. These loads include various static and dynamic loads, which are caused by operational, environmental and accidental conditions. The traditional methods of structural design attempt to account for the inevitable variability in the loads, material strengths, in-service environments, and fabrication process, etc., through the use of safety factors or load and resistance factors. These are prescribed in the various standards and specifications developed by such groups as ASME, ACI, AISC, etc. and the NRC Standard Review Plan (SRP). However, the subjective manner by which these safety factors have been determined may result in an unknown and nonuniform reliability (where reliability is defined as the probability that the structure will not fail during the projected lifetime).

The stochastic nature of loads and the variations in material properties dictate a probabilistic approach for a rational assessment of structural safety and performance. This means that the structures should be designed according to a required level of reliability. In recent years, an increasing effort has been directed toward the application of reliability analysis in conventional structures. In the nuclear industry also, there has been an increasing trend toward the utilization of the probability-based design and reliability analysis for safety evaluations.

This paper describes the results of a program undertaken by the Structural Analysis Division of BNL to develop, for the Nuclear Regulatory Commission (NRC), a rational approach based on probabilistic considerations for the safety evaluation of reactor containment and other seismic category I structures subjected to multiple static and dynamic loadings. Furthermore, based on the developed probabilistic approach, a load combination methodology for the design of seismic category I structures will also be established.

Benefits envisioned as a result of this work are:

1. establishment of probability-based load factors, load combinations and quantitative measures of structural safety;
2. insurance of consistent safety levels against various limit states; and
3. establishment of a tool for rational updating of design standards.

In this paper the main features of the reliability analysis methodology developed at BNL is reviewed first. While the methodology is intended for all seismic category I structures, the initial efforts were concentrated on reinforced concrete containment structures; thus, the methodology pertaining to these will be discussed. In order to demonstrate the feasibility of the method, results from reliability analysis of a realistic reinforced concrete containment structure under dead and live loads, accidental internal pressures and earthquake ground accelerations will be presented.

2. Structural Modeling and Limit States

For the reliability analysis of a reinforced concrete containment structure, a three-dimensional finite element model is utilized. A typical example of the model is shown in Fig. 1. The element utilized for the analysis is the shell element. It is described in the SAP-V computer code user's manual and hence need not be discussed here.

It is to be noted that in order to compute the limit state probability directly and conveniently, the structural modeling should be made in such a manner that the local coordinates of the element should have the same directions as those of the rebars.
A limit state essentially represents a state of undesirable structural behavior. In general it will depend on the characteristics of structures and the loadings that act on the structures. For a particular structural system, it is possible that more than one limit state has to be considered. Also, limit states must be specified in terms of the response quantities obtainable from the analysis performed on the selected structural model. For the numerical example to be presented later in the paper, the limit state is chosen to represent the onset of the flexural failure of the containment. At any time during the service life of the structures, the state of structural response is considered to have reached the limit state if the rebars begin to yield (in tension or compression) and/or is the crushing strength of the concrete is reached at the extreme fibers of the cross-section.

Analytically the limit state introduced above can be expressed as:

\[ f_s \leq f_y \]  

and/or

\[ f_c \geq 0.85 f'_c \]  

where \( f_s \) is the stress in the rebars and \( f_c \) is the compressive concrete stress at the extreme fibers.

Based on (a), the above definition of the limit state, (b) the assumption of a linear stress-strain relationship, and (c) the conventional theory of reinforced concrete, which asserts that concrete cannot take any tension, the limit state surface in terms of the membrane stress \( \tau \) and bending moment \( M \) can be established for a specific cross-section at the finite element boundaries. A typical limit state surface is shown in Fig. 2. In this figure "a" represents a limit state under pure (uniform) compression and point "b" represents a limit state under pure (uniform) tension. Also, straight lines I (ac and ac'), lines II (approximated by c'c and c'o'), lines III (ef and e'f') and lines IV (fg and f'g) indicate respectively those parts of the limit state surface in which the limit states are reached in concrete crushing with cross-sections remaining uncracked (lines I), in concrete crushing with partially cracked cross-sections (lines II), in yielding of rebars in tension with partially-cracked cross-sections (lines III) and yielding of rebars in tension with totally cracked cross-sections (lines IV). More details pertaining to constructing a limit state surface are given in an accompanying BNL paper presented elsewhere in this conference [1].

3. Loads and Structural Resistance

In order to carry out the reliability analysis of nuclear structures, it is essential to establish a data base for the various static and dynamic loads that act on the structures. These loads may be caused by operational, accidental or environmental conditions.

Data on environmental loads, such as tornado and earthquakes etc., were gathered and processed into proper probabilistic format by the National Bureau of Standards (NBS) for BNL [2,3]. Data on operational and accidental loads, on the other hand, are relatively scarce. The reason for this can be attributed to the short period of operation of nuclear power plants, to the proprietary nature of some of the pertinent data and to the lack of organized effort in assembling the data. Thus, BNL undertook a concensus estimation study of the operational and accidental loads acting on seismic category I nuclear structures. A draft report dealing with the results of this effort is currently under review by a peer committee [4].

Besides loadings, it is also necessary to establish a probabilistic model for the materials comprising the containment structure. Specifically, the yield strength of the linear,
rebars and compressive strength of concrete were established from test data. This effort is summarized in a report recently prepared for publication [5].

4. Reliability Analysis Methodology

As mentioned, the Structural Analysis Division of BNL has recently completed the development of a probability-based reliability analysis method for concrete containment structures. This method, which incorporates the finite element analysis and random vibration theory, makes it possible to evaluate the safety of the structures under various static and dynamic loadings in terms of limit state probabilities. In general, the method can evaluate the structural response to dynamic loads, which are characterized as stationary vector processes with specified cross-spectral density matrices. The 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 are Gaussian and therefore that the response is also Gaussian, techniques for estimating the rate at which the 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 these loads.

The reliability analysis method for dynamic loads is then combined with the existing standard reliability analysis procedure for static and quasi-static loads. The significant parameters that enter into the methodology are the occurrence rate, duration and intensity of each load (i.e., dead load, accidental internal pressure, earthquake, etc.). All these parameters are basically random variables for most of the loads to be considered. Currently, combination techniques for dead load, internal pressure and earthquake ground accelerations have been established. Details pertaining to the reliability analysis methodology are given in references [6, 7, and 8]. At the present time the methodology is being extended to include other loadings, such as tornado, thermal and hydrodynamic loads. The method is also being extended to other structures.

5. Numerical Example

In order to demonstrate the feasibility of the method, a reliability analysis of a realistic reinforced concrete containment structure under dead and live loads, internal pressures and earthquake ground accelerations, was carried out. Results for this typical structure are given below.

The containment structure chosen for analysis is depicted in Fig. 3. The containment consists of a circular cylindrical wall with a hemispherical dome on the top. The structure is considered fixed at the base. Dimensions used for the analysis are shown in Fig. 3. Rebar details are summarized in Table 1, while material properties are given in Table 2.

For this example, four types of loads are taken into consideration. They are dead and live loads (D/L), accidental internal pressures (P), and earthquake ground accelerations (E). The load parameters for these four loads are summarized in Table 3. Finally, the results of the reliability analysis are presented in Table 4.

From Table 4 it can be seen that the major contribution to the overall limit state probability comes from the combination D/L+P (7.23 \times 10^{-5}). The second largest contribution comes from the combination D/L+P_H (6.88 \times 10^{-5}). The combinations D/L+P_L+P_H and D/L+P_L+P_E produce limit state probabilities a few orders of magnitude smaller than those resulting from D/L+P and D/L+P_H in spite of the fact that the conditional limit state probabilities under D/L+P_L+P_E
D/L + P_{H} + E are as large as 10^{-3} and 10^{-1}, respectively. This is due to the extremely small expected number of simultaneous occurrences of P_{L} + E (1.90 x 10^{-6}) and of P_{H} + E (1.16 x 10^{-10}) during the expected service life.

6. Concluding Remarks

The probability-based reliability analysis methodology described in this paper was essentially developed during the last two years. An important feature of this methodology is the incorporation of finite element analysis and random vibration theory. By utilizing this method it is possible to evaluate the safety of nuclear structures under various static and dynamic loads in terms of limit state probabilities. While initial efforts were concentrated on reliability evaluations of reinforced concrete containment structures, efforts are now underway to make the methodology applicable to other types of seismic category I structures as well. Similarly, with respect to loads and load combinations, the developed methodology is being expanded so that other loads and load combinations acting on seismic category I structures can also be included in the probabilistic safety evaluations.

References


Acknowledgements

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### Table 1. Rebar Arrangement

<table>
<thead>
<tr>
<th>Location</th>
<th>Meridional Rebar</th>
<th>Hoop Rebar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical Shell</td>
<td>#18 @ 12&quot;</td>
<td>#18 @ 12&quot;</td>
</tr>
<tr>
<td>Dome (Lower Half)</td>
<td>#14 @ 12&quot;</td>
<td>2-#14 @ 12&quot;</td>
</tr>
<tr>
<td>Dome (Upper Half)</td>
<td>#14 @ 12&quot;</td>
<td>#14 @ 12&quot;</td>
</tr>
</tbody>
</table>

### Table 2. Material Properties

**Concrete**

- Weight Density: 150 lb/ft$^3$
- Young's Modulus: $3.6 \times 10^6$ psi
- Poisson Ratio: 0.2

91 Day Compressive Strength, $f'_c$

- Mean Value: 6086.6 psi
- Standard Deviation: 650.6 psi
- Distribution: Gaussian

**Rebars**

- Weight Density: 490 lb/ft$^3$
- Young Modulus: $29 \times 10^6$ psi
- Poisson Ratio: 0.3

**Yield Strength, $f_y$**

- Mean Value: 71.1 ksi
- Standard Deviation: 2.57 ksi
- Distribution: Gaussian
Table 3. Load Parameters (Expected Lifetime \(T = 40\) Years)

<table>
<thead>
<tr>
<th>Load</th>
<th>Load Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead &amp; Live Loads (D/L)</td>
<td>* Deterministic and time invariant</td>
</tr>
<tr>
<td>Internal Pressure (P_L) Due to a Large LOCA</td>
<td>* Occurrence rate (\lambda_{P_L} = 1.0 \times 10^{-4}/\text{year})</td>
</tr>
<tr>
<td></td>
<td>* Mean duration (u_{DP_L} = 10^6) seconds</td>
</tr>
<tr>
<td></td>
<td>* (P_L) = Gaussian with (\mu_{P_L} = 15) psi and (\sigma_{P_L} = 3) psi</td>
</tr>
<tr>
<td>Internal Pressure (P_H) due to Hydrogen Burn</td>
<td>* Occurrence rate (\lambda_{P_H} = 1.0 \times 10^{-5}/\text{year})</td>
</tr>
<tr>
<td></td>
<td>* Mean duration (u_{DP_H} = 600) seconds</td>
</tr>
<tr>
<td></td>
<td>* (P_H) = Gaussian with (\mu_{P_H} = 45) psi and (\sigma_{P_H} = 9) psi</td>
</tr>
<tr>
<td>Earthquake Load (E)</td>
<td>* Stationary random process (a segment of 10 seconds) with a Kanai-Tajimi spectrum</td>
</tr>
<tr>
<td></td>
<td>(S_{ggxx}(\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}; \omega_g = 9\pi \text{ rad/sec} )</td>
</tr>
<tr>
<td></td>
<td>(\zeta_g = 0.6)</td>
</tr>
<tr>
<td></td>
<td>* Distribution function of (Z = \frac{\xi}{\mu} )</td>
</tr>
<tr>
<td></td>
<td>(F_Z(z) = 1 - (z/\alpha)^{-1/2}; \alpha = 0.05g) and (\alpha = 2.61)</td>
</tr>
<tr>
<td></td>
<td>where (\alpha_g = p_g \sqrt{\mu_w (1/(2\zeta_g) + 2\zeta_g)}) with (p_g = 3.0)</td>
</tr>
<tr>
<td></td>
<td>* Occurrence rate (\lambda_E = 1.50 \times 10^{-2}/\text{year})</td>
</tr>
<tr>
<td></td>
<td>* Mean duration (u_{DE} = 10) seconds</td>
</tr>
</tbody>
</table>

Table 4. Lifetime Limit State Probabilities (\(T = 40\) Years)

<table>
<thead>
<tr>
<th>Load Combination</th>
<th>Expected Number of Occurrences (\lambda^{(\ast)})</th>
<th>Conditional Limit State Probabilities (p^{(\ast)})</th>
<th>Limit State Probabilities (p^{(\ast)})</th>
<th>Critical Finite Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>D/L</td>
<td>Always Acting</td>
<td>0</td>
<td>0</td>
<td>--</td>
</tr>
<tr>
<td>D/L + P_L</td>
<td>(4.00 \times 10^{-3})</td>
<td>Numerically Zero</td>
<td>(6.88 \times 10^{-5})</td>
<td>97, 98, \ldots, 120</td>
</tr>
<tr>
<td>D/L + P_H</td>
<td>(4.00 \times 10^{-4})</td>
<td>(1.72 \times 10^{-1})</td>
<td>(6.88 \times 10^{-5})</td>
<td>97, 98, \ldots, 120</td>
</tr>
<tr>
<td>D/L + E</td>
<td>(6.00 \times 10^{-1})</td>
<td>(1.21 \times 10^{-1})</td>
<td>(7.23 \times 10^{-4})</td>
<td>67, 18, 19</td>
</tr>
<tr>
<td>D/L + E + P_L</td>
<td>(1.90 \times 10^{-6})</td>
<td>(1.15 \times 10^{-3})</td>
<td>(2.20 \times 10^{-9})</td>
<td>67, 18, 19</td>
</tr>
<tr>
<td>D/L + E + P_H</td>
<td>(1.16 \times 10^{-10})</td>
<td>(4.24 \times 10^{-1})</td>
<td>(4.92 \times 10^{-11})</td>
<td>102, 103, 114, 115</td>
</tr>
<tr>
<td>Overall</td>
<td>--</td>
<td>--</td>
<td>(7.92 \times 10^{-4})</td>
<td>--</td>
</tr>
</tbody>
</table>
Figure 1 - Three-dimensional Model for Containment

Figure 2 - Limit State Surface

Figure 3 - Reinforced Concrete Containment Structure