ANALYSIS OF DRYWELL FLOOR SLAB FOR RANDOM LATERAL LOCA LOADS ON DOWNCOMERS

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In some Boiling Water Reactor containments, immediately after a loss of coolant accident (LOCA) chugging phenomena has been observed to occur in the tests. During chugging an oscillating condensation of steam takes place in the suppression pool which produces lateral loads on the downcomers. The magnitude of these loads is a random variable, the probability distribution of which can be ascertained by measurements. In addition, these loads have been observed to act on downcomers from all possible directions. Therefore, the direction from which these loads act is also a random variable, and it can be modeled by a uniform distribution between 0 to 2π.

These random loads on downcomers create random bending moments in the drywell floor slab which supports the downcomers. The purpose of this investigation is to obtain realistic values of these bending moments for which the slab could be designed. For the design of the slab usually the maximum possible bending moments are obtained by taking the highest value of the lateral load and assuming it to be acting on all downcomers in the directions to give highest moments in the slab. This obviously is a too conservative response value for design, as it disregards the randomness associated with the magnitude and direction of the force.

Herein a method which accounts for the randomness of magnitude and direction has been formulated to obtain the design moments. The moment influence lines were generated for an annular circular slab (representing drywell floor) and used to obtain moments at various sections of the slab due lateral force applied to the downcomers. The statistics of this bending moment (radial and circumferential) can be obtained in terms of the statistics of the load magnitude and direction. Probability distribution function for radial and circumferential moments can also be established. Since the total moment is sum of many random moments, its distribution function approaches normality. However, a more accurate description is also possible, as discussed in the paper. The design moments corresponding to a probability level of 10^-6 per year are obtained from the distribution functions. These moments are only about 56% of the maximum possible moments. A significant saving, therefore, can be achieved using this probabilistic approach.
1. Introduction

After a postulated loss of coolant accident (LOCA) in a boiling water reactor (BWR) the steam is discharged into the suppression pool through downcomers. During the condensation of steam some oscillating pressure waves in the water have been observed to occur in simulated tests. This phenomenon is often referred to as chugging. During chugging some randomly varying lateral loads have been observed to act on the submerged portions of the downcomers. They have also been observed to act on downcomers from all possible directions in a horizontal plane. These forces induce bending moments in the drywell floor slab which supports the downcomers at their top ends.

To design a drywell floor slab for the effects of these lateral loads, the practice has been to take the maximum value of the moment that can ever occur in the slab (i.e. the value with a probability of exceedance of 0.0) as the design moment. To obtain this moment, each downcomer is applied with the largest value of the lateral load in such a direction so as to give the maximum bending effect to the slab. This, obviously, gives a most conservative design value. This value disregards the randomness associated with the force magnitude and its direction of application. The design of the slab based on this high value of bending moment will be unnecessarily ultra conservative and, rather, unrealistic. A better and realistic design approach should rationally include the effect of randomness of the load magnitude and direction, and the design moment in such a situation should be chosen corresponding to an acceptably low level of risk. Such an approach is described here in this paper.

2. Analytical Formulation

Fig. 1 shows a drywell floor slab with a typical set of downcomers. Usually downcomers are arranged in circumferential rows and there may be three to four rows of downcomers in a drywell floor slab. The downcomers are rigidly attached to drywell floor slab at the top whereas at the bottom they are submerged in the suppression pool. The submergence depth in the water is about 2 to 4 feet. During chugging phenomena, the submerged ends of the downcomers are subjected to lateral loads with randomly varying magnitudes and directions. It is desired to obtain the radial and circumferential bending moments in the drywell slab due to these lateral loads.

Let $F_i$ be a lateral load acting at an angle $\theta_i$ from the reference axis on the $i$th downcomer (see Fig. 1). This force applies a point moment to the slab at the point where the downcomer is attached to the slab. If the lever arm of this force measured from the mid-plane of the slab is $h$, the applied radial and circumferential moments at the slab are, respectively,

$$M_r = h F_i \cos(\theta_i - \phi_i)$$

$$M_c = h F_i \sin(\theta_i - \phi_i)$$

(1)

in which $\phi_i$ is the angular position of the downcomer $i$. Due to these applied moments, the radial and circumferential bending moments induced at a point $P$ (Fig. 1) in the slab at a radius $r$ and angular location $\psi$ can be obtained using the influence coefficients as follows:

Radial moment,
\[ M^R_i(r, \psi) = R^R_i(r, \psi)M_r + C^R_i(r, \psi)M_c \]
\[ = hF_i a_i(r, \psi) \sin (\theta_i - \phi_i + u_i) \quad (2) \]

Circumferential moment,
\[ M^C_i(r, \psi) = R^C_i(r, \psi)M_r + C^C_i(r, \psi)M_c \]
\[ = hF_i b_i(r, \psi) \sin (\theta_i - \phi_i + v_i) \quad (3) \]

in which \( R^R_i(r, \psi) \) and \( R^C_i(r, \psi) \), respectively, are the radial and circumferential moment influence coefficients for an applied radial moment, whereas \( C^R_i(r, \psi) \) and \( C^C_i(r, \psi) \), respectively, are the radial and circumferential moment influence coefficients for an applied circumferential moment. These coefficients represent the bending moments induced at a point \((r, \psi)\) due to the unit moments applied at downcomer \(i\). The terms \( a_i(r, \psi) \), \( b_i(r, \psi) \), \( u_i \) and \( v_i \) in these equations are defined as follows:
\[ a_i(r, \psi) = \left[ (R^R_i(r, \psi))^2 + (C^R_i(r, \psi))^2 \right]^{1/2} \]
\[ b_i(r, \psi) = \left[ (R^C_i(r, \psi))^2 + (C^C_i(r, \psi))^2 \right]^{1/2} \]
\[ u_i = \tan^{-1}(R^R_i/C^R_i); \quad v_i = \tan^{-1}(R^C_i/C^C_i) \quad (4) \]

To obtain these influence coefficients, the influence lines are generated for all downcomer rows of the drywell floor slab. A set of influence lines generated for a row of the downcomers are shown in Figs. 2 through 5. Each figure shows the induced radial and circumferential moments at the points in the slab along the radial and circumferential reference planes passing through the point of application of the load. Thus if the point of interest is on one of these planes, these curves directly provide the required influence coefficients. However, if the point of interest is at the coordinates of \(r'\) and \(\psi'\) with respect to the point of application of the load, the influence coefficient for a particular moment effect (radial or circumferential) is obtained as a product of the influence coefficients values at \(r'\) and \(\psi'\) on the reference planes. Such influence lines can be generated by any finite element computer program. It may be noted that each row of downcomer requires a similar set of influence lines. In the numerical example considered here, the drywell slab had four rows of downcomers, thus, in all, 32 influence lines were generated to obtain the design moment in the slab.

For a linear analysis, the total moments at a point in the slab due to lateral loads on all downcomers can be obtained by superposition as follows:
radial moment:
\[ m_r(r, \psi) = h \sum_{i=1}^{N} P_i a_i(r, \psi) \sin (\theta_i - \phi_i + u_i) \quad (5) \]
circumferential moment:
\[ m_c(r, \psi) = h \sum_{i=1}^{N} P_i b_i(r, \psi) \sin (\theta_i - \phi_i + v_i) \quad (6) \]
where \(N\) is the number of downcomers influencing the slab at point \((r, \psi)\).
In Eqs. 5 and 6, \( F_i \) and \( \Theta_i \) are random variables. The probability density distribution of \( F_i \) is obtained by actual measurement of the force in a simulated post LOCA situation. The distribution of \( \Theta_i \) can be assumed to be uniformly distributed between 0 and 2\( \pi \) since no directional preference has been observed for these loads. It is also reasonable to assume that \( \Theta_i \)'s are statically independent of each other and \( F_i \). Also, all \( F_i \)'s are assumed to be identically distributed. With these assumptions, the statistical moments of the slab bending moments can be obtained from Eq. 5 and 6. For example, the means and variances of \( m_r \) and \( m_c \) are:

\[
\begin{align*}
E[m_r(r,\psi)] &= E[m_c(r,\psi)] = 0 \\
\text{Var}[m_r] &= \frac{1}{2} h^2 (\mu_F^2 + \sigma_F^2 \sum a_i^2) \\
\text{Var}[m_c] &= \frac{1}{2} h^2 (\mu_F^2 + \sigma_F^2 \sum b_i^2)
\end{align*}
\tag{7}
\]

where \( \mu_F \) and \( \sigma_F \) are the mean and standard deviation of \( F_i \).

To obtain the design moments corresponding to a probability level, the probability distributions of \( m_r \) and \( m_c \) are required. It may be rightly argued that they are normally distributed because these represent the sum of many independent bending moment effects induced by many downcomer loads (Eqs. 5 and 6). However, a more accurate description of the probability distributions in terms of the higher statistical moments of \( m_r \) and \( m_c \) is also possible.

For this purpose, the error between the actual distribution and its Gaussian approximation is expressed as a series of Hermite polynomials (Ref. 1) which constitute a complete orthogonal set in the interval of \(-\infty \) to \( \infty \). The coefficients of the series are then obtained in terms of the moments of the variable using the orthogonal property of the polynomials. Based on such an analysis, the expressions for the probability density, distribution, and inverse functions have been obtained for a sum of random variables. These are given in Ref. (2). To obtain the design moment corresponding to a probability of exceedance of \( p \), the following expression has been used in this paper,

\[
m_p = m_m + \psi_p \sigma_m
\tag{8}
\]

where \( m, m_m, \) and \( \sigma_m \), respectively, are the design, mean and standard deviation values of the bending moment. The factor \( \psi_p \) corresponding to the probability level \( p \) is obtained from the expression given in Ref. (2) on page 935 in terms of the statistical moments of the bending moment and Hermite polynomials as

\[
\psi_p = x + \gamma_2 \frac{H_3(x)}{24} + \gamma_4 \frac{H_5(x)}{720} - \gamma_2^2 \frac{3H_3(x)}{384} [3H_3(x) + 6H_5(x) + 2H_7(x)]
\tag{9}
\]

in which

\[
x = \Phi^{-1}(1-p);
\]

\[
H_n(x) = -\frac{1}{z(x)} \frac{d^n}{dx^n} z(x);
\tag{10}
\]

\[
z(x) = \exp(-x^2/2)/\sqrt{2\pi},
\]

where \( \Phi(x) \) is the standard normal distribution function. Also, \( \gamma_2 \) and \( \gamma_4 \) are defined in terms
of the statistical moments of the force as

\[
\gamma_2 = 3(m_2 - 2m_2^2) \sum_{i=1}^{N} a_i^4/(8s^4)
\]

\[
\gamma_4 = 5(m_6 - 9m_2m_4 + 12m_2^3) \sum_{i=1}^{N} a_i^6/(16s^6)
\]

\[
S^2 = m_2 \sum_{i=1}^{N} a_i^2/2
\]

in which \(m_n\) is the \(n\)th statistical moment of the lateral force. Eqs. 11 should be used when the radial design moment is required. To obtain the circumferential design moment, the \(a_i\)s in Eqs. 11 should replaced by \(b_i\)s.

3. Multiple Chugging Effect:

Multiple occurrences of chugging have been observed during condensation of steam in the suppression pool. Anywhere from 200 to 300 chugs (repetitive applications of lateral loads) may occur. The probability, \(P\), of the lateral load exceeding the design value in \(n\) occurrences can be written in terms of the probability, \(p\), of its exceeding the value in a single occurrence. That is,

\[
P = 1 - (1-p)^N
\]

(12)

To obtain the design moments for a target probability \(P\) the above equation is solved for \(p\) as

\[
p = 1 - \frac{1}{N} \ln(1-P)
\]

(13)

The magnitude of the design moment corresponding to this probability value can then be obtained from Eq. 8.

4. Numerical Results

The above approach has been used to obtain the design moment in a typical drywell floor slab, Fig. 1. The slab with four rows of downcomers has been analyzed. There are a total of 97 downcomers attached to the slab. The lateral load is assumed to act on each downcomer at a lever arm of 49'. The probability density function of the lateral force is assumed to be triangular, with limiting values of 1 kips and 7 kips, Fig. 6. Any other distribution or actually measured distribution can be used. In fact, in the approach used in this paper to obtain the design moment, only the statistical moments of the force are required. Also, as mentioned before, the direction of application of the load on a downcomer has been assumed to be uniformly distributed. The number of chugs per LOCA occurrence has been assumed to be 250.

Tables 1 and 2 show the values of the radial and circumferential moment at various radial sections of the slab. The design moment values are obtained for the probabilities of exceedance of \(10^{-2}\) and \(10^{-3}\) in 250 chugs. These probabilities correspond to the probabilities of \(4.02 \times 10^{-5}\) and \(4.02 \times 10^{-6}\) per chug, respectively. Also shown in the tables are the maximum possible values of the moment which could occur if all downcomers were subjected to the maximum lateral load (7.0 kips) applied in the most appropriate direction. These maximum possible values of the radial and circumferential moments can be obtained using the following equations:
\[
\begin{align*}
\text{Max } [m_c(r, \psi)] &= 7.0h \sum_{i=1}^{N} |a_i(r, \psi)| \\
\text{Max } [m_c(r, \psi)] &= 7.0h \sum_{i=1}^{N} |b_i(r, \psi)|
\end{align*}
\]  

(14)

It may be noted that the probability values in Tables 1 and 2 are conditional probabilities. That is, these are the probabilities of the load exceeding the given values, provided a LOCA occurs. To obtain total probabilities, the conditional probabilities should be multiplied by the probability of occurrence of the LOCA. The probability of occurrence of a LOCA has been estimated to be of the order of $10^{-4}$ (Ref. 3). Thus the values in the columns 3 and 4 of Tables 1 and 2 correspond to the probability levels of $10^{-5}$, and $10^{-7}$, respectively.

An acceptable practice in the design of nuclear power plant structures has been to omit a force from design considerations if its probability of occurrence per year is less than $10^{-7}$. Based on this, the forces in Column 4 are too improbable to be considered for the design of the drywell floor slab. Therefore, the moment values in column 3, corresponding to a conditional probability of $10^{-2}$, could be considered as plausible design values.

For the assumed shape of probability distribution of the force, it is seen that the largest design moment is only about 56% of the maximum value (in many cases this percentage is even smaller). Clearly, this percentage will be affected by the shape of the actual probability distribution of the force. For a highly skewed distribution to the right the design moment will be more near the maximum value. For example for a triangular distribution shown in Fig. 6b, this largest design moment was about 78% of the maximum moment. If the distribution is skewed to the left, this design value will be significantly lower than the maximum value. However, it seems appropriate to say that the maximum value is rather an unrealistic value to be considered for design. By giving due consideration to the randomness of magnitude and direction of the load, a more realistic, risk consistent value can be obtained with significant savings in the design cost.

References


### TABLE 1: RADIAL MOMENT IN THE DRYWELL FLOOR SLAB

<table>
<thead>
<tr>
<th>Section at Radial Distance</th>
<th>Maximum Possible Moment</th>
<th>Moment, Kips ft/ft</th>
<th>For Prob. of Exceedance Given LOCA</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>10⁻²</td>
<td>10⁻³</td>
</tr>
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<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
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<td>74.09</td>
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<tr>
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<td>43.59</td>
<td>48.93</td>
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<tr>
<td>496.0</td>
<td>72.94</td>
<td>34.68</td>
<td>39.12</td>
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### TABLE 2: CIRCUMFERENTIAL MOMENT IN THE DRYWELL FLOOR SLAB

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<th>Section at Radial Distance</th>
<th>Maximum Possible Moment</th>
<th>Moment, kips-ft/ft</th>
<th>For Prob. of Exceedance Given LOCA</th>
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<td>496.0</td>
<td>8.15</td>
<td>4.48</td>
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FIGURE 1 - DRYWELL FLOOR SLAB WITH A TYPICAL SET OF DOWNCOMERS

FIGURE 2 - INFLUENCE COEFFICIENTS IN RADIAL DIRECTION DUE TO RADIAL MOMENT AT THE RADIUS OF 279 INCHES

FIGURE 3 - INFLUENCE COEFFICIENTS IN CIRCUMFERENTIAL DIRECTION DUE TO RADIAL MOMENT AT THE RADIUS OF 279 INCHES

FIGURE 4 - INFLUENCE COEFFICIENTS IN RADIAL DIRECTION DUE TO CIRCUMFERENTIAL MOMENT AT THE RADIUS OF 279 INCHES

FIGURE 5 - INFLUENCE COEFFICIENTS IN CIRCUMFERENTIAL DIRECTION DUE TO CIRCUMFERENTIAL MOMENT AT THE RADIUS OF 279 INCHES

FIGURE 6 - ASSUMED PROBABILITY DENSITY FUNCTIONS FOR THE LATERAL LOAD