STRUCTURAL RELIABILITY EVALUATION OF AHWR INNER CONTAINMENT UNDER OVER-PRESSURIZATION

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ABSTRACT

Safety of containment for any nuclear power plant is of prime concern world over. In general, for any nuclear containment there may be significant variability in load and material resistances. Hence the confidence level in deterministic design needs to be ascertained. Therefore, containment safety against design basis accidents such as over-pressurization needs to be evaluated probabilistically. A non-linear finite element model analysis of the AHWR Inner containment structure is carried out using in-house code for accidental over-pressure. Different failure stages e.g. crack initiation, failure of concrete in tension, yielding of rebar and tendon were considered. Variability in concrete and steel material properties and over-pressure were considered. The inner containment being a complex structure hence its failure or performance function cannot be determined explicitly. Therefore, response surface techniques, in conjunction with series of finite element analysis, were used to determine the performance function. First order reliability method was used to determine the reliability indices at critical locations in the containment. These results will help to evaluate the realistic safety margins against over-pressurization. The paper presents the methodology adapted for probabilistic failure evaluation.

1. INTRODUCTION

Indian nuclear power plants have double containment with outer containment structure of reinforced concrete and inner containment structure of pre-stressed concrete. Containment is the ultimate barrier against release of any radioactivity to the public and plant personnel requires being safe against postulated design basis accidents (DBA). Loss Of Coolant Accidents (LOCA) due to the largest break in the high-energy primary piping system is one of the important DBA. Following LOCA the inner containment experiences high pressure. In order to avoid the leakages, the inner containment should withstand this pressure without any significant damage. In past such containments have been designed and analyzed using deterministic approaches. In such approaches one often goes for conservative assumptions in assigning material properties and factors of safety. However, in reality there is large variability in material properties and DBA pressure calculations. For overall safety assessment it is required to evaluate the probability of activity release to outside public that may occur following the DBA. Such an assessment essentially requires the data on probability of failure of containments. This paper presents a simple methodology for evaluating the probability of failure given that LOCA has occurred, using the methods of structural reliability. In the present work different failure stages e.g. crack initiation, yielding of rebar and tendon were considered. Variabilities in concrete and steel material properties and over-pressure were considered.

The structural reliability methods require the identification of failure surface or performance function. This function determines the dividing surface between the safe and failure domain. The reliability index is then determined based on these performance functions. The inner containment being a complex structure hence its performance function cannot be determined explicitly. Therefore, response surface techniques, in conjunction with series of finite element analysis, were used to determine the performance function. First order reliability method was used to determine the reliability indices for different failure stages.

2. PROBLEM DEFINITION

Advance heavy water reactor (AHWR) has a vertical configuration. Reactor building has double containments viz., inner containment of prestressed containment and outer containment of reinforced concrete. During the accident inner containment structure will be subjected to large internal pressure. The inner containment building has been designed for an internal pressure of 0.185 N/mm^2 (P_d).

2.1 Structural Failure Stages of AHWR

AHWR is a double containment system with inner containment (I.C.) being made of prestressed concrete and outer containment (O.C.) of reinforced concrete. During accident conditions large internal pressure occur in I.C. This over-pressurization may occur due to two reasons.

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1) Loss of coolant accident (LOCA) due to rupture of header
2) Rupture of main steam line

Ultimate structural failure of double containment system occurs in different stages. Due to over-pressurization of I.C., small cracks are formed, which further develop into large, crack openings. Then debonding of rebars or tendons happens, which leads to leakage of radioactive into annulus. With further increase in annulus pressure high altitude radioactive release through stack occurs and/or cracking in O.C. occurs. This will lead to release of radioactivity into environment.

2.2 Scope of the Present Work

In the present work different failure stages of Inner containment (I.C.) of AHWR against over-pressurization (LOCA) has been considered. The variabilities in material properties and LOCA pressure have been considered to find the probability at different failure stages of AHWR I.C.

3. FINITE ELEMENT MODELING OF INNER CONTAINMENT

3.1 Geometrical Modeling

The inner containment wall of AHWR is a prestressed structure with a cylindrical wall and tori-spherical dome. It is modeled using 8-noded 3D solid elements for concrete and 2-noded truss elements for reinforcing bars or rebars and tendons. To simulate the actual structure more closely, four solid elements are taken across the thickness, with the exterior elements forming the cover to the rebars. Rebar and tendon are modeled as discrete truss elements (instead of smeared shell element) located at inner edges of cover elements and at centre respectively. Lumping of bars is done to achieve equivalent areas of reinforcement in the actual structure. Only quarter containment is modeled since geometry and loading are symmetric. Therefore, symmetric boundary conditions are applied. Further, the portion of the structure above the raft has been considered in the analysis purpose.

3.2 Material Modeling

The materials used are concrete and reinforcing / prestressing steel. The M 45 grade concrete and Fe 415 grade reinforcement are used for AHWR inner containment. For steel rebars a plastic bilinear elastic-plastic material model is used. The hypo elastic material model, based on uniaxial stress-strain relationship that is generalized to take into account biaxial and triaxial stress conditions, is used for concrete. The concrete material model uses strain softening in compression and it also have failure envelope that defines cracking in tension and crushing in compression. In addition a smeared crack model is used to simulate cracking.

3.3 Material Properties

The material properties used for concrete and reinforcement/Prestress are described in Tables 1. The prestressing details are shown in Table 2.

3.4 Analysis Result

Through wall crack initiation in inner containment occurred at 2.30 times design internal pressure i.e. 2.30 P_d and rebar yielding occurred at 2.45 times design internal pressure i.e. 2.45 P_d.

4. STRUCTURAL RELIABILITY ANALYSIS OF AHWR INNER CONTAINMENT

Structural reliability of AHWR inner containment subjected to internal pressure against different failure stages e.g. crack initiation, yielding of rebar and tendon has been evaluated. The different performance functions have been obtained using response surface methodology. Finally probabilities of crack initiation and yielding of rebar/tendon, of AHWR inner containment given that LOCA has occurred have been evaluated.

4.1. Variability Considered in Probability Evaluation of Different Failures

In this work crack initiation and yielding of rebar/tendon are considered as failure. These failures involve number of random variables. Variability in concrete and steel material properties and LOCA pressure have been considered in the present analysis.

4.1.1 Variability in concrete material properties

Table 1: Material properties used for concrete and reinforcement/Prestress

Concrete:		Reinforcing Steel:	
Grade of Concrete	M 45	Young's Modulus of Elasticity	2.1×10^{11} N/m^2
Mean value of compressive strength (cube)	57.15 MP$_a$	Density	7850 kg/m^3
Ratio of cylinder to cube compressive strength	0.8	Strain hardening modulus	2.1×10^{9} N/m^2
Mean value of compressive strength (cylinder) $\mathbf{f_c'}$	45.72 MP$_a$	Yield Stress	415×10^{6} N/m^2
Characteristic strength (cube) $\mathbf{f_{ck}}$	45 MP$_a$	Prestressing Steel:	
Poisson ratio	0.2	Prestressing System	27 K13
Density	2500 kg/m^3	C/s area of prestressing cable	3583.8×10^{-6} m^2
Modulus of Elasticity $\left(21500\left(f_c'/10\right)^{1/3}\right)$	35684 MPa	Young's Modulus of Elasticity	2.1×10^{11} N/m^2
Maximum compressive stress	45.72 MPa	Strain hardening modulus	2.1×10^{9} N/m^2
Strain corresponding to maximum compressive stress	0.002	Ultimate Tensile Stress	1950×10^{6} N/m^2
Ultimate compressive strain	0.0035	Yield Stress	1560×10^{6} N/m^2
Ultimate compressive stress	28 MP$_a$	Rebar detailing:	Hoop direction / Meridional direction
Maximum tensile stress $\left(1.4\left(\left(f_c'-8\right)/10\right)^{2/3}\right)$	3.39 MP$_a$	Cylindrical wall	25@250Φ / 25@250Φ
Tension stiffening parameter **k** $(\mathbf{0.002/\varepsilon_{ct}})$	21.03753	Dome	20@200Φ / 20@200Φ

Table 2: Pre-stressing steel detailing:

No. of Hoop cables	105	No. of Dome cables	120 (60 in each direction)
Spacing of Hoop cables	550 mm	Initial strain in Hoop cable	4.56x10-^{3}
No. of Vertical cables	390	Initial strain in Vertical cable	5.07x10-^{3}
Spacing of Vertical cables	400 mm	Initial strain in Dome cable	4.8x10-^{3}

Average pre-stressing force in cables after all losses

Hoop cables	351.10 T
Meridional or vertical cables	390.67 T
Dome cables	370.01 T

The variability in the material properties of concrete occurs in spite of quality control during construction. The compressive strength of concrete is reported to follow lognormal distribution with coefficient of variation of 0.14 (refs [2, 3]). The other material properties are related with compressive strength e.g. tensile strength f_{ct} may be taken as $\left(1.4\left(\left(f_c' - 8\right)/10\right)^{2/3} \right)$ [4] and initial tangent modulus may be taken as $\left(21500\left(f_c'/10\right)^{1/3} \right)$ [4].

4.1.2 Variability in LOCA over-pressurization

LOCA pressure is assumed to be log-normally distributed. The mean value of LOCA pressure was taken as design pressure i.e.1.85 N/mm^2. The coefficient of variation is assumed to be 0.2. [5]

4.1.3 Variability in rebar material properties

Yield strength and strain hardening modulus of rebar is taken to be log-normally distributed with 10% standard deviation.

4.1.4 Variability in tendon material properties

Yield strength and strain hardening modulus of tendon is taken to be log-normally distributed with 5% standard deviation.

4.2 Structural Reliability Evaluation

AHWR inner containment has been analyzed against internal pressure. From deterministic analysis of inner containment wall it was concluded that the cylindrical wall, dome and regions of discontinuities are critical failure locations. In this paper crack initiation and yielding of rebar/tendon at cylindrical wall only has been considered. Since explicit equations were not available to directly formulate the limit state failure surfaces or performance functions, response surface method was used. The performance function sets the dividing surface between the safe domain and failure domain (of the form of R-S, where R is resistance / capacity and S is load / demand). If capacity of member is less than demand then the failure will take place. Thus $R \le S$ represents failure domain.

4.2.1 Response surface method

Quite often the structural capacity of complex structures and the demand cannot be easily defined by explicit formula and therefore failure surfaces can not be defined easily, for which failure surfaces may not be directly available. The present case of AHWR inner containment falls in that category. For such cases it is required to construct approximate performance function.

Response surface method is one such technique. Response surface methodology (RSM) is a set of techniques that encompasses:

1. Setting up (or designing) a series of experiments that will yield adequate and reliable measurements of the response of interest. For the present case experiment implies numerical experiments. Sets of finite element (FE) analyses were done to generate the response surface.
2. Determining a mathematical model that best fits the data collected from the design chosen in (1), by conducting appropriate tests of hypotheses concerning the model's parameters.
3. Determining the optimal settings of the experimental factors that produce the maximum (or minimum) value of the response.

Response surface method uses empirical approach and includes the application of regression analysis [6] as well as other techniques in an attempt to gain a better understanding of the characteristics of the response system under study. If $X_1, X_2, ..., X_k$ are input variables then true response function is continuous function of X_i and given by Eq. (1).

$$\eta = \phi\left(X_1, X_2, ..., X_k\right) \tag{1}$$

The general form of a second order quadratic model with k input variables $X_1, X_2, ..., X_k$ is given by Eq. (2) where Y is an observable response variable and $a_0, b_1, ..., b_k$ are unknown parameters, and ε is a random error term.

$$Y = a_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} c_i X_i^2 + \varepsilon \tag{2}$$

4.2.2 First Order Reliability Method (FORM)

First order reliability method (FORM) is used for finding probability of failure of components. FORM is based on the First Order Second Moment (FOSM) and Advanced First Order Second Moment (AFOSM) methods and applicable for normal as well as non-normal variables. The basic approach is to approximate the failure surface (expressed in standard normal variables) by a tangent plane at Maximum Probable Point (MPP), which is the first order approximation of Taylor's series about MPP. The algorithms for FORM [8] locate the design point on the failure surface (MPP), which is nearest to the origin in the standard normal space. This yields the reliability index (β). The probability of failure for a given failure surface is then equal to $P_f = \Phi(-\beta)$, where $\Phi(u)$ is standard normal cumulative distribution function.

4.2.3 Structural reliability of crack initiation

Structural reliability evaluation of AHWR inner containment subjected to internal pressure against crack initiation has been done. From deterministic analysis it can be easily concluded that crack initiation occurred at cylindrical wall. Therefore in this paper probability of crack initiation, given that LOCA has occurred, against over-pressurization is obtained only at cylindrical wall. The performance function has been obtained using response surface methodology. Six random variables i.e. compressive strength of concrete $\left(f_c'\right)$, yield strength of rebar $\left(f_y^R\right)$, strain hardening modulus of rebar $\left(E_{sh}^R\right)$, yield strength of tendon $\left(f_y^T\right)$, strain hardening modulus of tendon $\left(E_{sh}^T\right)$ and LOCA pressure (p) have been considered. Hoop stress (critical tensile stress under internal pressure) has been assumed to be response variable. The performance function for crack initiation at cylindrical wall has been obtained (/eq. (3)).

$$\mathbf{f_h} = -5.60+22.96\mathrm{p}+3.01\times10^{-6}\mathrm{f_y^R}+7.14\times10^{-4}\mathrm{f_c}'+0.525p^2-3.23\times10^{-6}\left(\mathrm{f_c}'\right)^2 \quad (3)$$

From equation (3) a plot between hoop stress (f_h) and pressure (p) it can be seen that critical tensile stress (hoop stress) is linear function of pressure only as expected for crack initiation. The performance function for this problem can be given by Eq. (4).

$$\mathbf{g} = 1.4\left(\left(\mathbf{f}_c'-8\right)/10\right)^{2/3} - \mathbf{f_h} \quad (4)$$

Now First Order Reliability Method (FORM) is applied to evaluate probability of crack initiation at cylindrical wall against over-pressurization. Mean LOCA pressure was varied from P_d to $3.5P_d$, where P_d is design pressure of AHWR i.e. 0.185 MP_a. Probability of crack initiation at cylindrical wall was plotted against mean LOCA pressure (Fig. 1). Probability of crack initiation at cylindrical wall increases as mean pressure increases.

4.2.4 Structural reliability of Yielding of rebar

Structural reliability evaluation of AHWR inner containment subjected to internal pressure against yielding of rebar has been done. One of the critical elements at cylindrical wall was chosen for the analysis. Plastic strain in rebar is function of compressive strength of concrete, yield strength of rebar and tendon, strain hardening modulus of rebar and tendon and LOCA pressure. This function is established using response surface methodology. Plastic strain in rebar exceeding specified range from 0% to 5.0% is considered to be limit state function for further reliability analysis. Six random variables i.e. compressive strength of concrete $\left(f_c'\right)$, yield strength of rebar $\left(f_y^R\right)$, strain hardening modulus of rebar $\left(E_{sh}^R\right)$, yield strength of tendon $\left(f_y^T\right)$, strain hardening modulus of tendon $\left(E_{sh}^T\right)$ and LOCA pressure (p) have been considered. Plastic strain in rebar has been assumed to be response variable. The response surface for plastic strain in rebar is obtained (Eq. (5)).

$$\begin{aligned}\boldsymbol{\varepsilon}_\mathbf{p}^\mathbf{R} &= 29.69-152.94\mathrm{p}-0.00215\mathrm{f_y^R}+0.00141\mathrm{f_c}'+4.51\times10^{-5}\mathrm{f_y^T}-8.58\times10^{-6}E_{Sh}^R+5.34\times10^{-6}E_{Sh}^T+197.92p^2\\&+1.79\times10^{-6}\left(\mathrm{f_y^R}\right)^2-2.74\times10^{-5}\left(\mathrm{f_c}'\right)^2-1.47\times10^{-8}\left(\mathrm{f_y^T}\right)^2+1.89\times10^{-9}\left(E_{Sh}^R\right)^2-1.30\times10^{-8}\left(E_{Sh}^T\right)^2\end{aligned} \quad (5)$$

Now First order Reliability Method (FORM) is applied for any given limiting value of rebar plastic strain (in %). Thus performance function for this problem can be given by Eq. (6).

$$\mathbf{g} = \boldsymbol{\varepsilon}_{\mathbf{p,lim}} - \boldsymbol{\varepsilon}_\mathbf{p} \quad (6)$$

Where $\boldsymbol{\varepsilon}_{\mathbf{p,lim}}$ varies from 0% to 5% and $\boldsymbol{\varepsilon}_\mathbf{p}$ is given by Eq. (5).

Probability of plastic strain in rebar exceeding limiting value of 0% to 5% has been obtained. This is plotted in fig. 2.

4.2.5 Structural reliability of Yielding of tendon

Structural reliability evaluation of AHWR inner containment subjected to internal pressure against yielding of tendon has been done. One of the critical elements at cylindrical wall was chosen for the analysis. Plastic strain in tendon is function of compressive strength of concrete; yield strength of rebar and tendon, strain-hardening modulus of rebar and tendon and LOCA pressure. This function is established using response surface methodology. Plastic strain in tendon exceeding specified range from 0% to 5.0% is considered to be limit state function for further reliability analysis. Six random variables i.e. compressive strength of concrete $\left(f_c'\right)$, yield strength of rebar $\left(f_y^R\right)$, strain hardening modulus of rebar $\left(E_{sh}^R\right)$, yield strength of tendon $\left(f_y^T\right)$, strain hardening modulus of tendon $\left(E_{sh}^T\right)$ and LOCA pressure (p) have been considered. Plastic strain in tendon has been assumed to be response variable. The response surfaces for plastic strain in tendon is obtained (Eq. (7)).

$$\boldsymbol{\varepsilon}_{\mathbf{p}}^{\mathbf{T}} = 173.04\text{-}563.01\mathrm{p}\text{-}0.00424\mathrm{f}_{\mathrm{y}}^{\mathrm{R}}\text{-}0.00154\mathrm{f}_{\mathrm{c}}'\text{-}0.059\mathrm{f}_{\mathrm{y}}^{\mathrm{T}} + 5.85\times10^{-5}E_{Sh}^{R} + 6.36\times10^{-4}E_{Sh}^{T} + 632.86\,p^2$$
$$+3.93\times10^{-6}\left(\mathrm{f}_{\mathrm{y}}^{\mathrm{R}}\right)^2 + 3.70\times10^{-6}\left(\mathrm{f}_{\mathrm{c}}'\right)^2 + 1.82\times10^{-5}\left(\mathrm{f}_{\mathrm{y}}^{\mathrm{T}}\right)^2 - 1.49\times10^{-8}\left(E_{Sh}^{R}\right)^2 - 1.53\times10^{-7}\left(E_{Sh}^{T}\right)^2 \quad (7)$$

Now First order Reliability Method (FORM) is applied for given limiting value of tendon plastic strain (in %). Thus performance function for this problem can be given by Eq. (8).

$$\mathbf{g} = \boldsymbol{\varepsilon}_{\mathbf{p,lim}} - \boldsymbol{\varepsilon}_{\mathbf{p}} \quad (8)$$

Where $\boldsymbol{\varepsilon}_{\mathbf{p,lim}}$ varies from 0% to 5% and $\boldsymbol{\varepsilon}_{\mathbf{p}}$ is given by Eq. (7).

Probability of plastic strain in tendon exceeding limiting value of 0% to 5% has been obtained. Limiting plastic strain in tendon has been plotted against probability of failure in Fig. 2. It is observed that the probability of exceeding any given strain is same for rebars and tendons.

5. RESULTS AND DISCUSSION

Structural reliability of AHWR inner containment under over-pressurization against different failure stages i.e. crack initiation, yielding of rebar and tendon has been carried out considering variability in material properties of concrete and steel, and LOCA pressure. Response surface methodology is used to formulate limit state functions for different failure stages. First Order Reliability Method (FORM) is applied to evaluate probability at different failure stages.

Probability of crack initiation at cylindrical wall against over-pressurization is evaluated. Mean LOCA pressure was

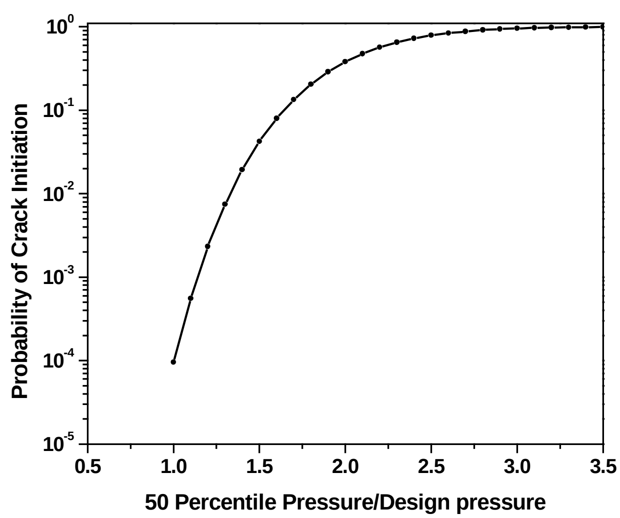

Figure 1: Probability of Crack Initiation at Cylindrical Wall against Pressure

parametrically varied from P_d to $3.5P_d$, where P_d is design pressure of AHWR i.e. 0.185 MP_a. Probability of crack initiation at cylindrical wall was plotted against mean LOCA pressure (Fig. 1). Probability of crack initiation at cylindrical wall increases as mean pressure increases. The probability of initiation of crack at design pressure is of the order of 10^{-4} per occurrence of the pressure of the magnitude of design pressure. The safety margin on design pressure is calculated using HCLPF (high confidence low probability of failure) values. The HCLPF pressure is the pressure which gives a probability of failure of 0.01 corresponds to the pressure at (50 percentile non exceedance pressure and pf = 0.01). This pressure comes out to be 1.4 times the design pressure. Thus the reliability analysis shows that additional safety margin exists compared to what is envisaged in deterministic design.

Probability of plastic strain in rebar/tendon exceeding limiting value of 0% to 5% has been obtained and plotted in fig. 2. The failure probability is conditional with respect to existence of LOCA. The probability of failure is while considering 0.5% -5% yielding in tendon or rebar is calculated as $2x10^{-6} – 6x10^{-7}$ per occurrence of design pressure.

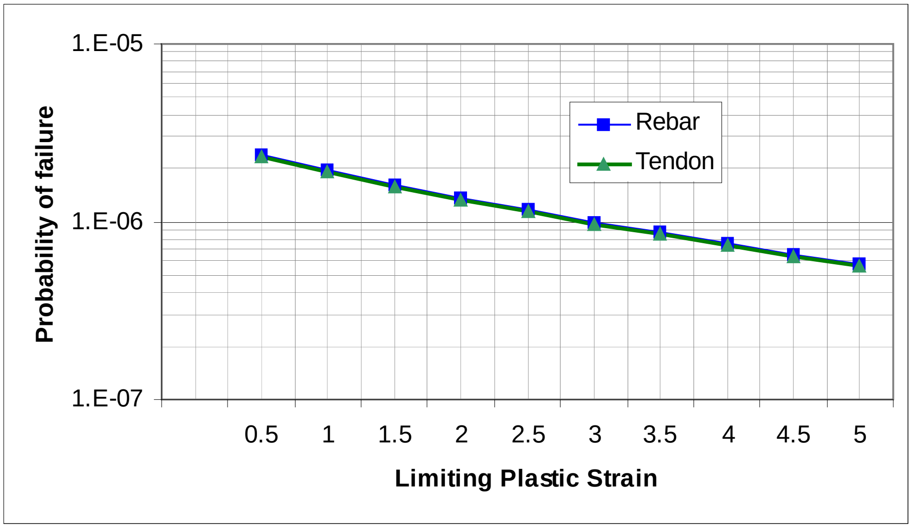

Figure 2: Probability of failure

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