Reliability of Prestressed Concrete Containment Structure Against Internal Pressure

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ABSTRACT

Possible failure modes of a prestressed concrete containment structures (PCCS) under the action of internal pressure are hoop tension; bending plus membrane stress at extreme fiber at wall-raft junction; shear near the edge and fixture on basement; and punching shear near large penetrations like airlocks. Amongst these, hoop tension at principally membrane region is reported to be the predominant one. The paper assesses the reliability of PCCS against hoop tension failure adopting first order second moment method of level-2 reliability analysis. The performance function, g (.), was formulated on the basis of standard design format of prestressed concrete containment structure for hoop tension induced by internal pressure. Three basic variables considered are internal pressure, ultimate strength of prestressing tendons and compressive strength of concrete. Short-term as well as time dependent long-term prestressing losses are taken into account in formulating g (.). Both epistemic and aleatory uncertainties associated with basic variables are considered. It is observed from the analysis results that reliability of a prestressed concrete containment structure deteriorates with age. It is also noted that uncertainties associated with ultimate strength of prestressing cable have maximum effect on failure probability where as that due to internal pressure and compressive strength of concrete have moderate and negligible effects respectively. Rational estimation of prestressing loss is very important for safety of the containment structure over the entire operating life.

INTRODUCTION

Design requirement for prestress concrete containment structure is governed by determination of adequate prestressing force to neutralise the effect of internal pressure caused by loss of coolant accident event or hydrogen explosion. Safety of the containment structure, especially against the internal pressure, greatly depends on rational assessment of minimum residual prestressing force available during the entire span of its operating life.

A prestressed concrete structure losses its prestressing force over the age. This loss can be classified into two types, namely, short-term losses and long term losses. The short-term losses are due to anchorage slip, elastic shortening of the structure and friction and wobble effect. These losses occur immediately after stressing the cable and are time invariant. The shrinkage and creep of concrete and relaxation of prestressing cable contributes to long term prestressing losses. These are time dependent phenomenon and results in significant losses of prestressing force in the containment structure over a period of time.

In the present paper, attempt is made to analyze the reliability of prestressed concrete containment structure under the action of internal pressure taking into account of both short term and long term prestressing losses.

RELIABILITY OF CONTAINMENT STRUCTURE

Reliability of a structure is the complement of its probability of failure due to design loads. Common approach to assess reliability of a reinforced or prestressed concrete structure is to determine its probability of failure at the limit state condition, which is also sometime called as limit state probability of the structure. The limit state probability is the probability of structural response that will reach the limit state condition under the action of design loads during the operation life. It is the unconditional probability of failure of overall structure, P_f, under the action of postulated load combinations for given operation life T. Following Sinozuka et al [1], the reliability of a reinforced concrete containment structure is assessed as follows,

$$P_f = \sum_{L=1}^{N} P_{fL} \tag{1}$$

Where,

N = number of load combinations,

P_{fL} = failure probability for a given load combination L

$$= P_f^L \bigcap P_r^L \tag{2}$$

P_f^L = conditional structural failure probability due to load combination L

$$= Max.\left[P_{f-e,m}^L\right] \tag{3}$$

Eq.(3) is applicable for load combination without earthquake load. For load combination involving earthquake load, P_f^L is given by,

$$P_f^L = Max.\left[\sum_m P_{f-e,m}^L\right] \tag{4}$$

$P_{f-e,m}^L$ = conditional probability of failure of the e[th] element due to m[th] failure mode under the action of L^{th} load combination

P_r^L = probability of occurrence of load combination L

$$= T\lambda^L \tag{5}$$

Unconditional probability of failure, P_f, is obtained combining Eq.(1), (2) and (5)

$$P_f = T\sum_{L=1}^{N}\lambda^L P_f^L \tag{6}$$

In Eq.(5) and Eq.(6), operation life of the structure is T year and λ^L is the expected rate or the annual frequency of occurrence of load combination L. It is assumed that the independent loads $l_1, l_2, \ldots l_i, \ldots, l_N$ of L^{th} load combination occur simultaneously and each of them arrives in accordance with the Poisson law with the expected arrival rate of λ_i and each occurrence lasts for an average period of μ_i. Shinozuka et al [1] also showed that if deal load (DL) and Live Load (LL) is combined with other independent loads then λ^L is

$$\begin{aligned}
&\lambda^L = \lambda_i\,, && \text{for } L = DL + LL + l_i \\
&\lambda^L = \lambda_i\lambda_j(\mu_i + \mu_j), && \text{for L = DL + LL + } l_i + l_j,\ i \neq j \\
&\lambda^L = \lambda_i\lambda_j\lambda_k\left(\mu_i\mu_j + \mu_j\mu_k + \mu_k\mu_i\right), && \text{for } L = DL + LL + l_i + l_j + l_k,\ i \neq j \neq k
\end{aligned} \tag{7}$$

In case of containment structures, examples of these individual loads, l_i, are pressure load, earthquake load, wind load, etc.

Shinozuka et al [1] developed their methodology for calculation of $P_{f-e,m}^l$ for a reinforced concrete containment structure with the following limit state functions,

$f_s \geq f_y$ *and* $f_c \geq 0.85f_c'$

Where, f_s, f_y, f_c and f_c' are stress in rebar, yield strength of rebar, compressive stress (at extreme fiber) and specified compressive strength of concrete respectively. It was assumed that stress-strain relationships of materials are linear in nature and concrete would not take any tension. The above limit state formulation may be viewed corresponding to performance function (PF) representing failure mode of membrane plus bending induced in the reinforced concrete containment structure under the action of applied load.

RELIABILITY OF PRESTRESSED CONCRETE CONTAINMENT STRUCTURE

For prestressed concrete containment structures, the resistance at a given age against any loading effect is dependent on the residual prestressing available in the structure at that age. Therefore, it is a function of the age of structure resulting P_f^L also to be a function of age. The unconditional failure probability at an age '*t*' can be calculated from Eq.(6) as follows,

$$P_{f,t} = \sum_{L=1}^{N}\lambda^L \int_0^t P_{f,a}^L\,da \tag{8}$$

Where, the $P_{f,a}^L$ is the conditional probability of failure due to load combination 'L' at age 'a' and is determined from Eq.(3) and Eq.(4). As $P_{f-e,m}^L$ is also dependent on age, it is represented as $P_{fa-e,m}^L$ in further calculations.

The conditional probability, $P_{fa-e,m}^L$ of prestressed concrete containment structure is determined in the present work by optimising the performance function (PF) of appropriate failure modes using first order second-moment method (FOSM) of level-2 reliability analysis [2,3]**.** This calls for identification of failure modes of the system. Possible failure modes of a prestressed concrete containment structures under increasing internal pressure are:

1. Hoop tension: yielding of prestressing cable.
2. Bending plus membrane stress at extreme fibber at wall - raft junction.
3. Shear near the edge and fixture on basement.
4. Punching shear near the large penetration like airlocks.

Shunmugavel and Gurbuz [4] studied evaluation of ultimate load capacity of six prestressed concrete containment vessels (PCCV) of pressurised water reactor based nuclear power plant. Under internal pressure load, hoop tension failure away from discontinuities and at about mid height were found to be the most predominant failure mode of a PCCV. Test conducted on a 1:4 scale model PCCV subjected to increasing internal pressure also revealed failure by rupturing of hoop tension at about mid height away from the discontinuities [5]. The containment structure is assumed to be in the threshold of limit state if the hoop tension induced by the internal pressure begins to cross the hoop strength of the containment structure. Unlike RC containment structure, the limit state function corresponding to any failure mode of a prestressed concrete containment structure is time dependent. Therefore, the limit state function of a prestressed concrete containment structure for mode of failure under hoop tension is,

$$p_a \geq A_s\left(f_{pu} - \Delta_{fpl}(t)\right)/R \qquad (9)$$

Where,
p_a = pressure load per unit height
A_s = Area of prestressing steel per unit height
f_{pu} = ultimate strength of prestressing tendons,
$\Delta_{fpl}(t)$ = total loss of prestressing force at the age *t*,
R = radius of containment.

Eq.(9) is based on standard linear design format of a prestressed concrete containment structure for hoop tension induced by internal pressure. The limit state would effectively occur in case the pressure load crosses radial force induced by the residual force in prestressing cable. The residual prestressing force at a given age depends on the initial prestress and the prestressing loss. Normally the tendons are initially prestressed to a lower level of stress, ~80% of the ultimate strength. The current study considers the initial prestressing force in the cable to be equal to the ultimate strength of the tendon. This approach is expected to provide the upper bound estimate of structural reliability.

Concrete is assumed not to withstand any tensile stress. The effect of gravitational load like dead load and live load on induced hoop tension is ignored and contribution of the passive reinforcement to the hoop tensile strength is considered negligible. This simplification is rational for a prestressed concrete containment structures for two reasons. Firstly, passive reinforcement generally provided in areas predominantly subjected to membrane stress is not based on strength requirements. It is provided following the codal requirements of minimum reinforcement. Its contribution toward hoop tension resistance is minimal. Secondly, whatever small effect of dead load and live load has on the induced hoop tension would compensate the impact of not consideration of the contribution of passive reinforcement to the hoop strength of the containment structure.

From Eq.(9), performance function of hoop tension failure mode, $g(.)$,

$$g(.) = \frac{A_s\left(f_{pu} - \Delta_{fpl}(t)\right)}{R} - p_a \qquad (10)$$

Where, total prestressing loss, $\Delta fpl(t)$, at a give age t is given by

$$\Delta_{fpl}(t) = \Delta_{fpls} + \Delta_{fpll}(t), \qquad (11)$$

Δ_{fpls} = short term loss

$$= \Delta_{fpl1} + \Delta_{fpl2} + \Delta_{fpl3}, \qquad (12)$$

$\Delta_{fpll}(t)$ = long term prestressing loss

$$= \Delta_{fpl4}(t) + \Delta_{fpl5}(t) + \Delta_{fpl6}(t) \qquad (13)$$

Δ_{fpl1} = presterssing loss due to anchorage slip,
Δ_{fpl2} = prestressing loss due to elastic shortening of the structure,
Δ_{fpl3} = prestressing loss due to friction and wobble effect,
$\Delta_{fpl4}(t)$ = prestressing loss due to shrinkage of concrete,
$\Delta_{fpl5}(t)$ = prestressing loss due to creep of concrete, and
$\Delta_{fpl6}(t)$ = prestressing loss due to relaxation of steel.

All the terms of Eq.(12) and Eq.(13) are determined from two key material properties f_{pu} and f_c for a given configuration of the containment structure.

STATISTICAL PROPERTIES OF BASIC VARIABLES

In formulation of performance function $g(.)$, the basic variables are p_a, f_{pu} *and* f_c. Statistical properties of basic variables have strong bearing on the reliability of structures. These properties are taken into account by means of probability density function and specifying suitable mean value and standard deviation. Basu and Templeman [6] showed the importance of appropriate consideration of the statistical properties in structural reliability analysis. Uncertainties, both aleatory and epistemic, associated with basic variables are also important. Epistemic uncertainty is caused due to inherent randomness of associated with the basic variables and aleatory uncertainty is related to incomplete knowledge of these variables, design and construction process phenomenon. These uncertainties does not seem to be separately treated by Shinozuka et al [1], Hwang et al [7] and Schëller [8] whereas Cornel [9] and, Ravindra and Galambos [10] treated explicitly both types of uncertainties in their work. The model code, JCSS [11] also suggests treating these two uncertainties separately. In the current study, both these uncertainties are treated separately.

Uncertainties are generally considered in terms of coefficient of variation (*cov)*, which is ratio of standard deviation and mean value. Epistemic uncertainties (*cov:* v_T) in p_a is due to inherent randomness of the load, while the aleatory type (v_E) emanates from inadequate knowledge of model for deriving the loading effect from phenomena like LOCA, hydrogen explosion; the assumption made in modeling ofstructural analysis; and induced loading effects in members. Total uncertainties in loading effect (v_P) is,

$$v_P^2 = \left(v_T^2 + v_E^2\right) \tag{14}$$

Total uncertainties associated with the strength parameter of an structural element, for example hoop strength of the containment structure, consist of variability in material strength, (v_M), design process (v_D) and construction process (v_C). Total uncertainties in strength (v_Q),

$$v_Q^2 = v_M^2 + v_D^2 + v_C^2 \tag{15}$$

v_D and v_C are associated with structural element not with the basic variables of individual material strength f_c and f_{pu}. For calculation of these parameters, current study has adopted the following approach. The equivalent contribution from material strength of each basic variables like f_{ck}, f_{pu} to combined uncertainty due to those associated with design and construction process is,

$$v_{CD} = \alpha\left[\left(v_C^2 + v_D^2\right)^2 \div n\right]^{0.5} \tag{16}$$

Where, n is the number of individual materials and α is a constant. Its value considered in the present work is 0.8. Therefore, total uncertainties associated with the individual material strength v_m,

$$v_m^2 = \left(v_M\right)_m^2 + \left(v_{CD}\right)^2 \tag{17}$$

EXAMPLE

Containment structure

Cross-section of the containment structure considered to in this study as the example problem is depicted in Fig.1. The containment structure consists of a circular cylindrical wall capped with segmented hemispherical dome. Springing level is at height of 54.825m above the top of base raft. Thickness of containment wall is 750mm and that of dome is 380mm. Both the wall and dome are made off prestressed concrete and base raft is of RCC material. Areas of prestressing cable per unit height are 9657 and 6300 mm^2 respectively in circumferential and longitudinal direction

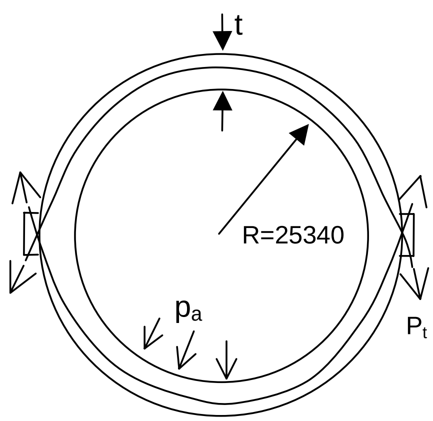


Fig.1: Cross Section of Prestressed Concrete Containment Structure.

Accidental internal pressure load

The internal pressure load, p_a, due to LOCA is assumed to be as quasi-static in nature and uniformly distributed over the internal surface of the containment structure. The characteristic value of the load is taken as 0.146 MPa. Shinozuka et all [1] considered cov as 0.2 for p_a, arising out of both LOCA and hydrogen explosion. Hwang et al [7] used two values of coefficient of variation, 0.12 and 0.2 of p_a, for their work. But, there is hardly any information on epistemic and aleatory uncertainties, v_E and v_T for internal pressure load in published literature. For v_E, JCSS [11] suggests the range 0.05 - 0.2 for dead load and live load, while Cornel [9] used the value of 0.1 for this. In the present work, the range of values considered are 0.1 – 0.2 for both v_E and v_T. The occurrence rate for internal pressure λ_{Pa} is taken as 10^{-4} per year.

Materials

The cube compressive strength of concrete is 45 MPA and corresponds to M45 grade. The characteristic value of the ultimate strength prestressed cable is 1861 MPa. The coefficient of variation of different parameters for compressive strength of concrete and prestressing cable are selected from literature [3, 9, 11]. The values used in the present work are given in Table 1.

Performance function

The parameters $\Delta_{fpls}, \Delta_{fpl4}, \Delta_{fpl5}$ and Δ_{fpl6} of Eq.(6) and Eq.(7) are derived for the containment configuration and using the provision of AERB safety standard on design of concrete structures [12,13].

$$\Delta_{fpls} = 0.175 f_{pu} + 97.5$$

$$\Delta_{fpl4} = 0.1985x(576.0 - 4 f_{ck})\left\{\left[\frac{(t-14)}{(t+19673)}\right]^{o.5} - 0.062\right\}$$

$$\Delta_{fpl5} = 0.0107 f_{pu} \frac{50.79}{(0.8 f_{ck} + 8)^{0.5}} \frac{(t-90)}{(t+1334)}$$

$$\Delta_{fpl6} = 0.02k_t(0.625 f_{pu} - 97.5), \; k_t = (0.024t)^{0.19} \leq 3.0$$

Statistical parameters of basic variables fck, fpu and pa are summarized in Table 2.

Table 1: *cov* given in literature on different types of uncertainties associated with resistance

cov	Cornel[9]	JCSS[11]	Ranganathan[3]	IS 456[14]
v_M	Concrete: 0.09	Concrete: 0.06	Concrete (M20-25): 0.15 Rebar: 0.1 Prestressing. Steel: 0.073	Concrete (M45) : 0.11
v_C	0.06 – 0.10	Varying mean deviation & standard deviation	Varying mean deviation & standard. deviation	
v_D	0.07	Bending: 0.15, Shear: 0.10, and Buckling: 0.25	-	

Table 2:Statistcal parameters of basic variables

Basic variables	Characteristics value (MPa)	Mean value (MPa)	*cov*	
			Reference value	Range
Concrete, f_{ck}	45.0	53.3	0.19	$0.16 – 0.24^{\#}$ $(0.173 – 0.226)^{*}$
Prestressing steel, f_{pu}	1861.0	2116.0	0.18	$0.16 – 0.22^{\#}$ $(0.163 – 0.219)^{*}$
Pressure load, p_a	0.146	0.117	0.18	$0.18 – 0.30^{\#}$ $0.141 – 0.283)^{*}$

\# range considered in analysis, * calculated range using Eq.(16), Eq,(17), and Table-1

RESULT AND DISCUSSION

The conditional probability calculated using the performance function of Eq.(9) corresponds to the conditional probability P_{fa}^{L} of Eq.(3). The hoop tension failure mode is most predominant failure mode under the action of internal pressure and this induces maximum tensile stress in hoop direction at about mid height of the containment structure. The resulting conditional failure can be taken as the maximum value of P_f^l Eq.(3).

To examine the influence of probability distribution function (PDF) of pressure loading, analyses are carried out for following two cases of PDF for basic varibles,

Case-1 f_{ck}: Normal (N), f_{pu}: Normal (N), p_a: Normal (N)
Case-2 f_{ck}: Normal (N), f_{pu}: Normal (N), p_a: Log-normal (LN)

Paramatric study is conducted to examine the influence of *cov* of f_{ck}, f_{pu} and p_a on the failure probability for both the above cases. The results are plotted in Fig 2, 3 and 4 respectively for both the cases, Case -1 and Case-2.

It is observed from the figures that assumption of normal distribution or long normal distribution for internal pressure load results in generally insignificant difference in the values of conditional probability of failure P_f^L.

The effect of variability in f_{pu} is found to cause maximum difference in probability of failure, Fig.2. The value varies from 1.0^{-5} at the beginning to 1.0^{-3} at end of 100 years, Fig.2. The rate of increase in conditional probability of failure over age is found to be decreasing with increase in values of covariance, Figs.2a and 2 b. Variation in conditional probability due to different values of v_{fck} is almost nil, Fig. 3. The effect of v_{pa} is also not significant, Fig-4. Irrespective of type of input parameter, consideration of a covariance of about 0.18 resulted in almost similar estimation of conditional probabilities of failure.

The contribution of DL and LL to the hoop tension is negligible and rate of occurrence of load combination (DL + LL + p_a) is same as that of p_a, Eq.(6). Therefore, the unconditional probability calculated from Eq.(7) is, in fact, tends to be the failure probability of the containment structure against the load combination of (DL + LL + p_a). The unconditional probability, $P_{ft}^{DL+LL+p_a}$, of the containment structure is calculated taking reference value of *cov* of basic variables and is plotted in Fig.5. It is observed that it varies from 1.0^{-9} at the beginning to 1.0^{-5} at 100 years. At 40 years, the value is higher than 1.0^{-6}. Here, also the PDF of P_a has almost no influence on unconditional failure probability. These estimated values of unconditional failure probability are the lower bounds as full f_{pu} is taken as the initial level of prestress.

The probability of failure of prestressed concrete containment structure estimated in this paper is quite different than that calculated by Shinozuka et al [1] for reinforced concrete containment structure. Failure probability for both types of containment structure is very low initially but it increases substantially with age for the prestressed one. This is because hoop strength of a prestressed concrete containment structure against the internal structure is principally offered by prestressing force, which deteriorates with time. Therefore, it is very important to assess rationally prestressing loss with time for the safety of containment structure against accidental pressure load.

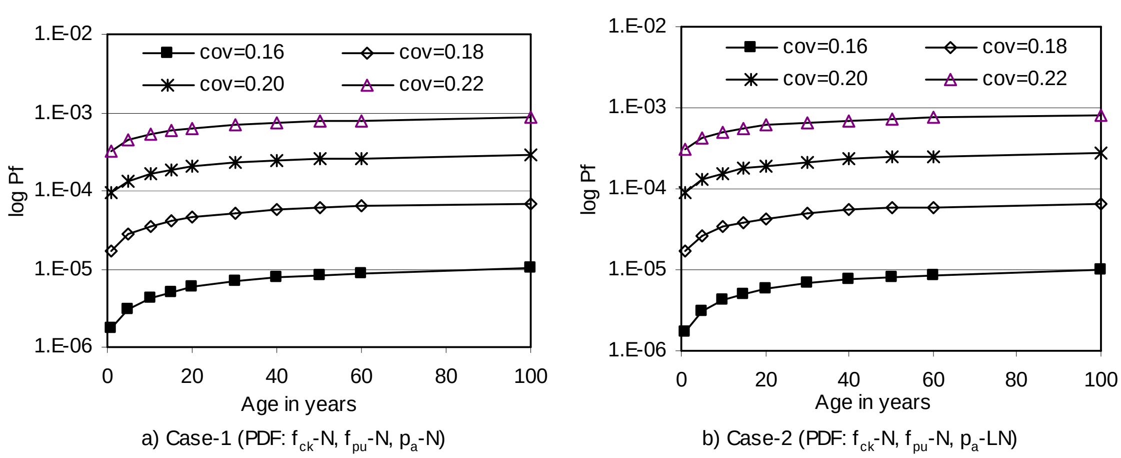
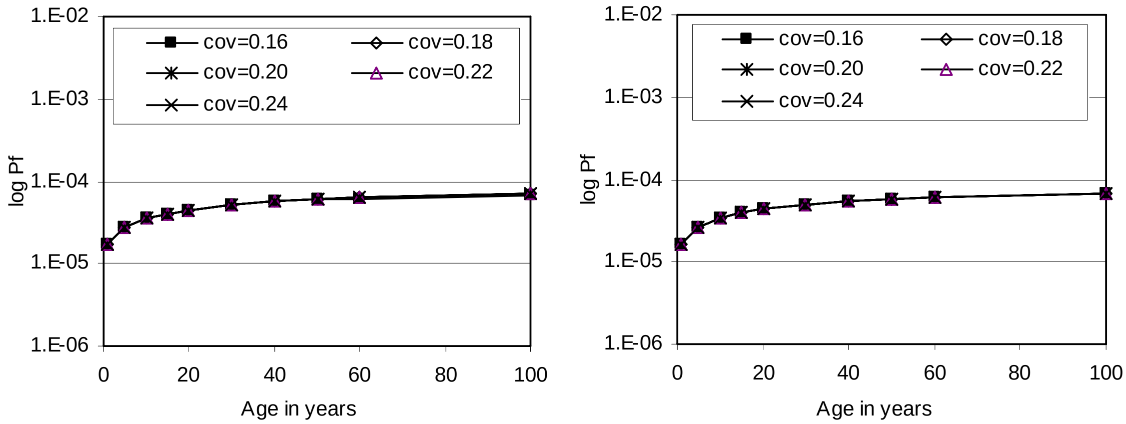
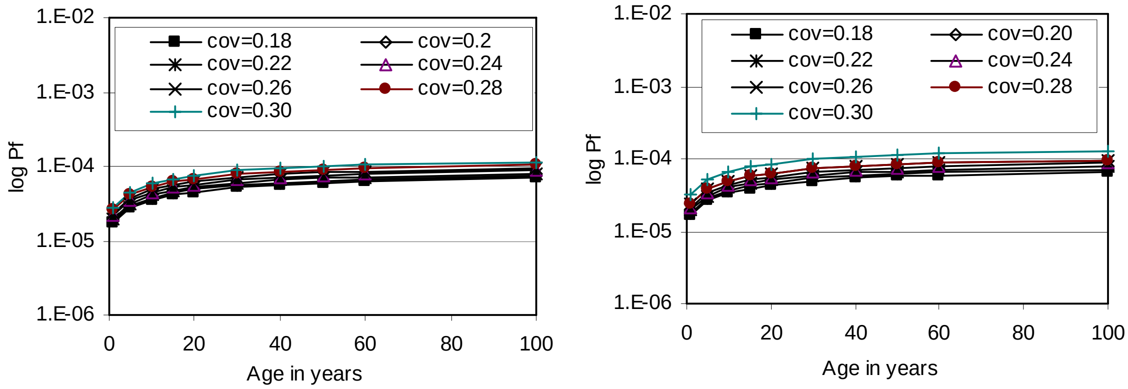


Fig.2: Variation of Conditional Probability P_f^L with Age for Different Values of Vf_{pu}



a) Case-1 (PDF: f_{ck}-N, f_{pu}-N, p_a-N) b) Case-2 (PDF: f_{ck}-N, f_{pu}-N, p_a-LN)

Fig.3: Variation of Conditional Probability P_f^L with Age for Different Values of Vf_{ck}



a) Case-1 (PDF: f_{ck}-N, f_{pu}-N, p_a-N) b) Case-2 (PDF: f_{ck}-N, f_{pu}-N, p_a-LN)

Fig.4: Variation of Conditional Probability P_f^L with Age for Different Values of Vp_a

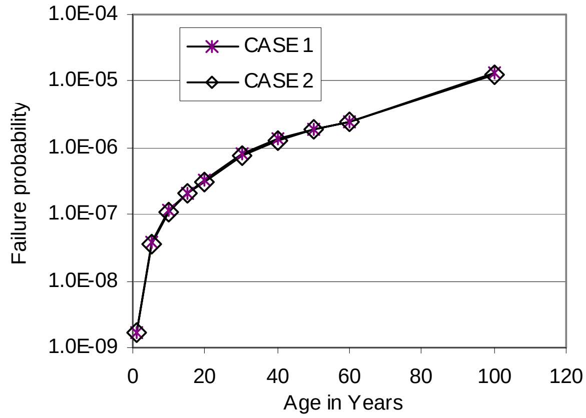


Fig.5: Total Probability of Failure of the Containment Structure for Hoop Tension Mode of Failure

CONCLUSION

- A simple methodology is developed for reliability assessment of prestressed concrete containment structure against internal pressure loading. Both epistemic and aleatory uncertainties of basic variables are treated separately in the method.

- Failure probability of a prestressed concrete containment structure against pressure loading is higher than that of RCC containment structure.
- Co-efficient of variation of the ultimate strength of prestressing cable has significant bearing on the failure probability of prestressed concrete containment structure. Influence of co-efficient of variations of other basic variables is generally insignificant, so also that of probability density function of pressure load.
- The results indicate that it is very important to rationally assess the prestressing loss for safety of prestressed concrete containment structure during entire span of its operating life.

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