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Structural reliability of pre-stressed concrete containments

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ABSTRACT

This paper presents probabilistic analysis of structural capacity of pre-stressed concrete containments subjected to internal pressure. The conventional design methods for containments are based on allowable stress codes which ensure certain factor of safety between expected load and expected structural strength. Such an approach may give different values of structural reliability in different situations. In recent years, two international round robin exercises have been conducted aimed at predicting the capacity of lined and unlined pre-stressed concrete containments used in nuclear industry. These exercises involved experimental testing and numerical analysis of the models. The first exercise involved 1/4 scale steel-lined Pre-stressed Concrete Containment Vessel (PCCV) which was tested at Sandia National Laboratories (SNL) in USA. The second used an unlined containment being tested by the Bhabha Atomic Research Centre (BARC), Tarapur, India. These studies are essentially deterministic studies that have helped validate the analysis methodology and modelling techniques that can be used to predict pre-stressed concrete containment capacity and failure modes. The paper uses these two examples to apply structural reliability method to estimate the probability of failure of the containment.

The two international round robin exercises have already established the ultimate structural collapse mode of the containments under internal pressure loading which indicate that the failure takes place in the general field of the containment wall around mid-height and away from any major structural discontinuities like the penetrations. This is because robust design procedures have been used to avoid structural failure at discontinuities by providing adequate compensation. Based on these experimental studies and the attendant numerical analyses a failure function is presented that assumes first yielding in the hoop direction at mid-height of the cylinder wall. A failure function equating the free-field membrane hoop stress to the hoop strength as a function of cross-sectional area (per unit height) and yield stresses of concrete, rebar, liner plate and tendons is developed.

First Order Reliability Method (FORM) is applied to predict probability of failure of the containments. Probability of failure vs internal pressure is presented for both types of containments. The paper presents a simple method to establish structural reliability of a pre-stressed concrete containment which can be useful for probabilistic safety assessment when considering extreme events that lead to over-pressurisation of the containment. The FORM approach was validated by comparison to the results of analogous calculations using Subset Simulation and Importance Sampling techniques for Monte Carlo simulation. It was found that at high pressures the Advanced FORM approach yields a good approximation to the true probability of failure.

The sensitivity of the probability of failure to the assumed coefficients of variation of properties of the containment was studied using the Sobol and Total Sensitivity Indices. At design pressure it was found that the coefficients of variation of the tendon yield and tendon area are the most important parameters followed by the applied pressure and containment radius. At higher pressures it was found that the coefficients of variation of the applied pressure and containment radius are the most important parameters. The variability of the probability of failure is decreased at higher pressures, but the coefficients of variation still play an important role.

Abbreviations: BARCOM, Bhabha Atomic Research Centre (BARC) Containment test model; CoV, coefficient of variation; FEA, Finite Element Analysis; FORM, First Order Reliability Method; PCCV, Pre-stressed Concrete Containment Vessel; SNL, Sandia National Laboratories.

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1. Introduction

A pre-stressed concrete containment is an important safety related structure as it acts as one of the final barriers to radioactive release. These structures are normally designed in accordance with the allowable stress codes to sustain the specified loading conditions. However, the compliance with the industry standard allowable stress codes does not give any reliable indication of the probability of failure (P_f) if the containment is over-pressurised under postulated beyond design basis events. In the past few years, two international round robin exercises have been conducted which have provided valuable test data related to failure under over-pressurisation. The first exercise involved the numerical analysis of the 1/4 scale steel-lined Pre-stressed Concrete Containment Vessel (PCCV) with design pressure (Pd) of 0.39 MPa which was tested at Sandia National Laboratories (SNL) in USA and has been analysed by Prinja and Shepherd (2003). The second exercise involved the unlined Bhabha Atomic Research Centre (BARC) Containment test model (BARCOM) with Pd of 0.1413 MPa that is being tested by the BARC in Tarapur, India and has been analysed by Kamatam and Prinja (2011). These studies are essentially deterministic studies that have helped validate the analysis methodology and modelling techniques that can be used to predict pre-stressed concrete containment capacity and failure modes. Such deterministic analytical and experimental studies have helped to establish the mode of failure but do not give any indication of P_f. Furthermore, the conventional allowable stress codes used to design such containments also do not provide P_f information. The aim of this paper is to present a simple method to establish structural reliability of a pre-stressed concrete containment which can be useful for probabilistic safety assessment when considering over-pressurisation under extreme events.

The method used to perform the analysis was Advanced FORM, a computationally efficient approximate method. In addition, Sensitivity Analysis was used in order to justify some arbitrary parameters used in the structural reliability analysis. Sensitivity Analysis is the process of attributing the uncertainty in the output of a mathematical model to the different sources of uncertainty in its inputs. In this paper we determine the sensitivity of the probability of failure of a concrete containment vessel to the assumed coefficients of variation of input parameters to the structural reliability analysis. These input parameters are physical properties of the containment. Before the sensitivity analysis was completed, the FORM method was validated for the containment at the design pressure and at 5.4 times the design pressure to provide an indication of the credibility of the FORM. This calculation was performed by comparing the results from the FORM to the true value of the probability of failure obtained from Subset Simulation and Importance Sampling as it was found that the failure probability was too small to be evaluated in a short time using standard Monte Carlo simulation. Once this was completed the parameters whose variance had the greatest contribution to the variance of the output were determined using the Sobol and Total Sensitivity indices, and the effect on P_f of varying these parameters was considered in greater detail.

2. Failure mode

Both SNL and BARCOM tests have shown that the collapse of the containment structure subjected to internal pressure is not expected to occur soon after the design pressure is exceeded. There is no 'cliff edge' but a gradual progressive damage of the containment structure under over-pressurisation which indicates safety margin against collapse. The structure may suffer local failures leading to functional failure well before the ultimate structural collapse. The experiments and the attendant numerical analyses have established the ultimate structural collapse mode of the containments under internal pressure loading which indicates that the failure takes place in the general field of the containment wall around mid-height and away from any major structural discontinuities like the penetrations. This is because robust design procedures have been used that provide adequate compensation and

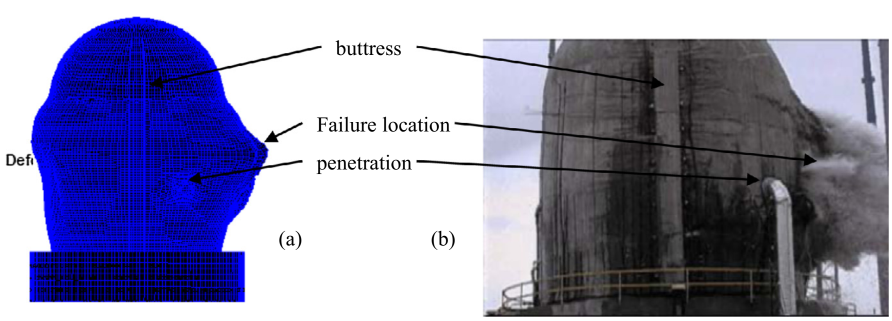

Fig. 1. Predicted failure mode of the SNL model (a) FEA results vs (b) test at P = 3.65 Pd.

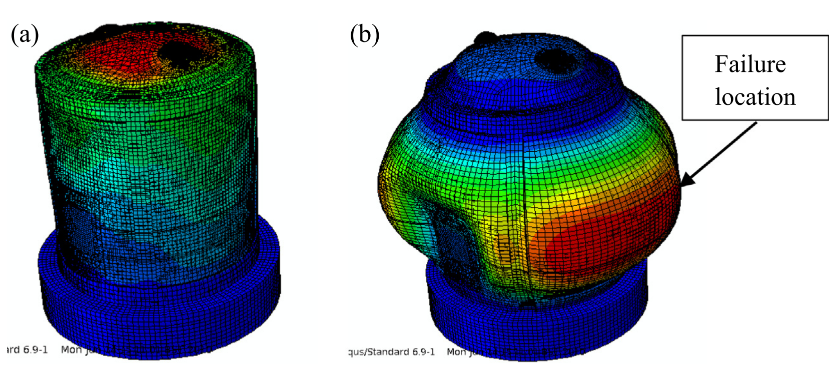

Fig. 2. Predicted response of the BARC model (a) under prestress only and (b) at P = 2.89 Pd.

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