ARTICLE IN PRESS

Nuclear Engineering and Design xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Assessment of Ultimate Load Capacity of concrete containment structures against structural collapse

Moloy K. Chakraborty *, Sourav Acharya, Ajai S. Pisharady, A.D. Roshan, L.R. Bishnoi

Siting & Structural Engineering Division, Atomic Energy Regulatory Board, Mumbai 400094, India

A R T I C L E I N F O

Article history:
Received 30 September 2016
Received in revised form 25 June 2017
Accepted 27 June 2017
Available online xxxx

Keywords:
Containment
Finite Element Method
Hermetic boundary
Non linear analysis
Ultimate Load Capacity

A B S T R A C T

Nuclear safety regulations in India require assessment of containment structure for Ultimate Load Capacity (ULC) for internal pressure. ULC and associated behavior of containment is evaluated with respect to various performance indicators based on defined criteria. Non-linear FE analysis of the containment structures was carried out considering non-linear material properties of concrete and steel using ABAQUS and ANSYS software. Evaluation of ULC was undertaken to understand containment performance under severe accident conditions, as a round robin analysis based on 1:4 containment model test results conducted at SANDIA national Lab, USA. AERB also participated in the international round-robin exercise organized by BARC to assess the ULC of BARC's containment test model (BARCOM). The test model is a 1:4 scale replica of 540 MWe PHWR pre-stressed concrete inner containment structure of Tarapur Atomic Power Station Units 3&4. Based on the knowledge gained from these studies VVER 1000 reactor building constructed at Kudankulam (KKNPP) was assessed for ULC of its primary containment as a regulatory requirement. VVER containment study was first of its kind as it is a lined containment with cellular basement structure. Non-linear FE analysis in ABAQUS using layered shell model was performed to assess the ULC of the containment structure. Three times of design pressure is estimated to be ULC of the structure.

1. Introduction

Containment structure is the last engineered barrier against release of radioactivity into public domain in case of a postulated accident. AERB safety code on design (AERB/SC/D) (Atomic Energy Regulatory Board (AERB), 2009) requires the containment to be designed taking into account all identified design basis accidents. In addition, features for mitigating consequences of severe accidents need to be provided. One of the recommendations stemming from this requirement is the evaluation of Ultimate Load Capacity (ULC) of the containment structure. Elaborating the above requirement, AERB safety guide AERB/NPP-PHWR/SG/D-21 (Atomic Energy Regulatory Board (AERB), 2007) requires that structural integrity of the containment structure including major appurtenances against collapse should be demonstrated by calculating the ULC considering both pressure and temperature loads. ULC of a containment structure should not be less than the maximum peak pressure calculated for potential severe accidents or twice the design pressure, whichever is higher (Atomic Energy Regulatory Board (AERB), 2007).

AERB participated in round robin exercises for evaluating ULC of scaled down model of containment structures to develop confidence in computationally exhaustive simulation and its validation through experimental results. AERB's participation in these exercises is summarized in subsequent sections (Sections 2 and 3). Evaluation of ULC of real life containment (VVER) through numerical simulation was done using the methodology, established through these participations. In present study VVER containment

List of abbreviations: AERB, Atomic Energy Regulatory Board; BARC, Bhabha Atomic Research Centre; BARCOM, BARC Containment Model; BDBA, Beyond Design Basis Accident; CDP, Concrete Damage Plasticity; DBA, Design Basis Accident; DEC, Design Extension Condition; EAL, Emergency Air Lock; EP, Embedded Part; FE, Finite Element; FEA, Finite Element Analysis; IC, Inner Containment; KKNPP, Kudankulam Nuclear Power Plant; MAL, Main Air Lock; NPCIL, Nuclear Power Corporation of India Limited; NPP, Nuclear Power Plant; NUPEC, Nuclear Power Engineering Corporation; PCCV, Primary Concrete Containment Vessel; P_d, Design Pressure; PDHRS, Passive Decay Heat Removal System; PHWR, Pressurized Heavy Water Reactor; PSC, Pre-stressed Concrete; PWR, Pressurized Water Reactor; RCC, Reinforced Cement Concrete; RG, Regulatory Guide; SRP, Standard Review Plan; SNL, Sandia National Laboratory; TAL, Transport Air Lock; TAPS, Tarapur Atomic Power Station; ULC, Ultimate Load Capacity; USNRC, United States Nuclear Regulatory Commission; VVER, Voda Voda Energo Reactor.

* Corresponding author.
E-mail address: mkchakraborty@aerb.gov.in (M.K. Chakraborty).

http://dx.doi.org/10.1016/j.nucengdes.2017.06.046
0029-5493/

Please cite this article in press as: Chakraborty, M.K., et al. Assessment of Ultimate Load Capacity of concrete containment structures against structural collapse. Nucl. Eng. Des. (2017), http://dx.doi.org/10.1016/j.nucengdes.2017.06.046

structure, which is a lined containment with cellular basement, is analyzed to predict its ULC. Evaluation of ULC of a lined containment with cellular basement monolithic with outer containment and annex parts, has been attempted for the first time in India.

There is always a demand from industry to assess the Ultimate Load Capacity of nuclear containment structure (being the last barrier from core to environment) for beyond design basis internal overpressure, specifically after the accident at Three Mile Island nuclear plant. Sandia National Laboratory (SNL) is involved in various experimental studies on structural integrity of steel, concrete and prestressed concrete containment for 'beyond design basis accident' (BDBA) or 'design extension condition' (now a days, DEC) accident scenario (Hessheimer and Dameron, 2006). Global involvement in the field of ULC of containment was evident from round robin exercise of 1:4 scaled model NUPEC/NRC Prestressed Concrete Containment Vessel (PCCV) Model Test in SNL. During last decade evaluation of ULC of containment structure has been a requirement of design assessment in different reactor designs in India. Nuclear Power Corporation of India Limited (NPCIL) had undertaken evaluation of ULC for containment structures of PHWR series constructed in India. Bhabha Atomic Research Center (BARC) of India participated in a pre-test analysis of the round-robin exercise of 1:4 scaled model in SNL. BARC carried out ULC analysis using in-house analysis software, ULCA (Basha et al., 2003). This software uses a number of concrete layers across the shell thickness along with different reinforcement patterns to accommodate the steel reinforcement with smeared approach. The compression yielding and crushing are predicted with the help of concrete compression strength using Drucker-Prager theory. The softening behavior of concrete is predicted with the help of tension stiffening. Failure mode investigation was done for both prestress cable slip and liner tear, where best and upper bound estimate of ultimate capacity (3.15 Pd and 3.45 Pd) was based on liner tearing near equipment hatch and lower estimate (2.75 Pd) was prestressing cable slippage.

BARC also conducted a test on 1:4 scaled model of Indian PHWR inner containment structure (BARCOM) and numerical prediction was also carried out.

NPCIL assessed ULC of containment structure of standard 220 MWe Indian PHWR containments (Roy, 2012). The concrete behavior in tension was modeled using a stress based cracking criterion in conjunction with a smeared crack model. Tension stiffening behavior was simulated by gradual release of concrete stress component normal to the crack plane. To account for aggregate interlock and dowel action in the smeared crack model, appropriate cracked shear modulus is assumed as a function of tensile strain. Concrete in compression was modeled as an elastic-perfectly plastic model by providing an appropriate yield criterion and flow rule. Functional capacity of these plants were also estimated along with their structural integrity. The functional failure criteria was defined as a through thickness crack width 0.2mm. Estimated functional failure was 1.85 P_d, where as structural capacity was noted as 1.97 P_d (Roy, 2012). For containment structure of 540 MWe PHWR at TAPS-3&4, the ULC against functional and structural failure were reported as 1.88 P_d and 2.08 P_d respectively (Ray et al., 2003).

Knowledge development in the field of containment responses for design extension condition was also demanded in AERB. So, AERB participated in round robin exercise on BARCOM test and AERB-USNRC standard problem exercise (SPE-3). AERB extended the scope of this type of analyses through its participation in the USNRC standard problem exercise "Performance of containment vessel under severe accident conditions" (Heitman et al., 2014). In addition to evaluation of ULC, analytical studies using local FE models also addressed effect of containment dilation on the existing prestressing force, slip of prestressing tendons, steel-concrete interface behavior, failure mechanisms and use of in-situ material properties. For the first time, containment leakage rate was estimated as a function of pressure and temperature. Summary of main findings from the round robin exercises undertaken by AERB and their implementation in present work are outlined in following sections.

2. Evaluation of ULC of 1:4 scaled steel lined PCCV

SANDIA National Laboratory of USA conducted a test program for capacity assessment of prestressed concrete pressure vessel (PCCV) with participation from around the globe in the form of round robin exercise. AERB and USNRC jointly conducted a Standard Problem Exercise-3 (SPE-3) regarding containment performance under severe accident conditions as a round robin analysis. The analysis was based on 1:4 containment model test results carried out at SANDIA national Lab, USA (Hessheimer et al., 2006). The exercise was done in two phases. In phase-I, evaluation of ULC was done, and also structural behavior of containment around discontinuities was predicated. In phase-II, containment leakage rate was estimated as a function of pressure and temperature for beyond design basis accident conditions for the first time, which was not attempted analytically for the entire containment in any of the earlier round robin exercises. In this exercise (SPE-3), other than AERB and USNRC/SNL, teams from EDF, FORTUM, GRS and SCANSCOT were also participated (Heitman et al., 2014).

PCCV model is 1:4 scale replica of Ohi-3 nuclear power plant in Japan. The PCCV model consists of a 10.8 m diameter cylinder with wall thickness of 325 mm, a 3.5 m thick raft/base mat and a hemispherical dome of thickness 275 mm (Hessheimer et al., 2006). For evaluating ULC of this PCCV, AERB carried out non-linear structural analysis using ABAQUS® FEA software (ABAQUS-6.12, 2012) by modeling the structure using 4-noded layered shell element. Steel reinforcements were simulated as smeared steel layers with thickness equal to the ratio of the rebar area to the rebar spacing. Prestressing tendons were also modeled as smeared steel layers. Liner was modeled as an integral layer attached to concrete. Fig. 1 shows the finite element (FE) model of the containment, where 13900 numbers of FE elements with various sectional properties (different color codes) are shown.

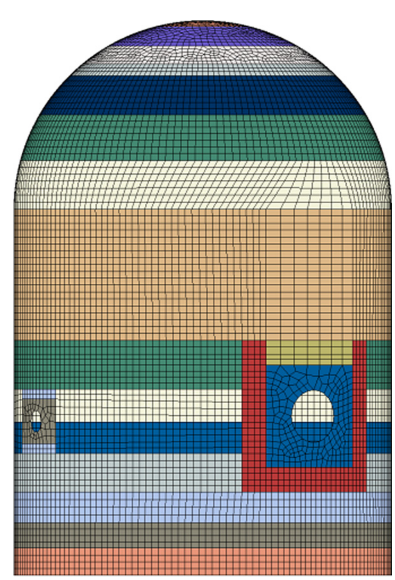

Fig. 1. Finite element model of PCCV 1:4 scaled model.