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Over-pressure test on BARCOM pre-stressed concrete containment

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A B S T R A C T

Bhabha Atomic Research Centre (BARC), Trombay has organized an International Round Robin Analysis program to carry out the ultimate load capacity assessment of BARC Containment (BARCOM) test model. The test model located in BARC facilities Tarapur; is a 1:4 scale representation of 540 MWe Pressurized Heavy Water Reactor (PHWR) pre-stressed concrete inner containment structure of Tarapur Atomic Power Station (TAPS) unit 3&4. There are a large number of sensors installed in BARCOM that include vibratory wire strain gauges of embedded and spot-welded type, surface mounted electrical resistance strain gauges, dial gauges, earth pressure cells, tilt meters and high resolution digital camera systems for structural response, crack monitoring and fracture parameter measurement to evaluate the local and global behavior of the containment test model.

The model has been tested pneumatically during the low pressure tests (LPTs) followed by proof test (PT) and integrated leakage rate test (ILRT) during commissioning. Further the over pressure test (OPT) has been carried out to establish the failure mode of BARCOM Test-Model. The over-pressure test will be completed shortly to reach the functional failure of the test model. Pre-test evaluation of BARCOM was carried out with the results obtained from the registered international round robin participants in January 2009 followed by the post-test assessment in February 2011. The test results along with the various failure modes related to the structural members – concrete, rebars and tendons identified in terms of prescribed milestones are presented in this paper along with the comparison of the pre-test predictions submitted by the registered participants of the Round Robin Analysis for BARCOM test model.

1. Introduction

Over more than three decades, the demonstration of robust containment design has become important for the public acceptance of nuclear power plants, which needs to be verified through the functional and structural failure mode tests. The earlier beyond design basis accidents at Three Mile Island-1979 (USA) and Chernobyl-1986 (former USSR) and more recently at the Fukushima-2011 (Japan) nuclear plants have led to wide attention on the ultimate load capacity assessment of nuclear containments structures. The design, safety and regulatory requirements demand ruling out containment structural failure by design measures and hence an adequate factor of safety over the design pressure has been emphasized (see for example Liersch et al. (1994), Davies et al. (1995) and review of various Sandia model tests reported by Hessheimer and Dameron (2006)). The assessment of old containment structures and design and safety assessment of new nuclear containments need to follow the standard practice of the pre-stressed concrete reactor vessel design philosophy of ASME design code section III Div-2 (ASME Boiler and Pressure Vessel Code, 2007), where a factor of safety of 2 is assured over the design basis accident.

The ultimate load capacity assessment of all the nuclear plants in India has been carried out over the years using in-house computer codes ULCA and ARCOS-3D in Bhabha Atomic Research Centre (BARC). These codes have earlier been extensively used to predict the ultimate load capacity of 220/540 MWe PHWR containment designs and a factor of safety ~2.3–2.5 over the design pressure has been demonstrated (Singh et al., 1993; Gupta et al., 1995). BARC, Trombay also participated in the round robin analysis of Pre-Stressed Concrete Containment Vessel (PCCV) of a typical PWR steel lined pre-stressed concrete containment sponsored by Sandia National Laboratory, USA and Nuclear Power Engineering Corporation, Japan during the pre-test phase (PCCV, 1997). The predictions made by BARC in-house finite element code ULCA, developed by Singh et al. (1993) and Basha et al. (2003a) were found to be in excellent agreement with the observed and published test results, as reported in Basha et al. (2003a,b) and Singh (2007).

Further for the ultimate load capacity assessment of Indian PHWR nuclear containments, 1:4 size BARC Containment (BARCOM) Test Model (Fig. 1) representing 540 M We PHWR pre-stress concrete inner containment with design pressure (Pd) of 0.1413 MPa has been constructed and commissioned at Tarapur site (BARC, 2006; Singh et al., 2009). Under this containment safety research program initiated at BARC Trombay for Indian PHWRs, BARCOM performance is being evaluated with the international round robin analysis results obtained from 15 registered participants during the pre-test and post-test phases (Singh, 2009, 2011a).

The objective of the present test program is to obtain the pressure, displacement and strain data related to the various functional and structural failure modes of BARCOM in terms of the loss of pre-stress in the membrane and discontinuity regions of major openings, first appearance of concrete surface cracks followed

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by first through thickness cracks, first yielding of reinforcement/tendons and significant loss of leak tightness, the maximum pressure sustained by the model before significant leakage to identify functional failure pressure of the test-model and finally the maximum static pressure sustained by the model for the structural failure assessment. All these assessments would finally lead to the estimation of the functional and structural behavior of the containment model up to the ultimate pressure for beyond the design basis severe accident studies.

The experiments on BARCOM Test Model have been planned in the following four phases:

1. Phase I – Calibration of sensors during low pressure test (LPT)-limited up to 0.35 Pd.
2. Phase II – Proof test (PT) and Integrated leakage rate test (ILRT) up to 1.0 Pd.
3. Phase III – Over pressure test (OPT) up to the Functional Failure of model.
4. Phase IV – Ultimate load capacity test (ULCT) of BARCOM.

The Phase-I pressurization of BARCOM Text Model up to 0.049 MPa (0.35 Pd) was carried out for the functionality tests of various sensors and data logger systems consisting of 350 surface mounted electrical resistance strain gauges (SMERs), 768 vibratory wire strain gauges (VWSGs), 32 dial gauges, 9 potentiometer based dial gauges, 20 Tilt-meters, 17 RTDs, and 17 earth pressure cells installed on the BARCOM. Fig. 1 gives an overview of various embedded sensors in BARCOM along with an exhaustive cable work up to the Control & Instrument (C&I) Building. Subsequently, BARCOM Test-Model was pressurized up to the design pressure (Pd) of 1.44 kg/cm^2 (0.1413 MPa) on August 06, 2010 at 01.00 AM and since then three more design pressure tests have been completed during October–December, 2010 under the Phase-II experiments. The commissioning and Proof Test of BARCOM has been completed successfully and data from all the sensors were recorded during the pressurization and depressurization cycles. In addition, consistent and repeatable leakage-rate was obtained during all the Phase-II experiments. Further under the Phase-III over-pressure test (OPT) program, the BARCOM Test Model was pressurized up to a pressure of 0.2207 MPa (1.56 Pd) on December 17, 2010. The milestone with regard to "first appearance of crack" was recognized with online monitoring of the inelastic strain developed in the discontinuity regions of Main Air Lock (MAL) and Emergency Air Lock (EAL) with embedded VWSGs, which was also confirmed with soap bubble test during depressurization at 0.0981 MPa. A second OPT was also conducted during January 12–15, 2011 to check the repeatability of the test data and obtain the localized strain field in the fracture process zone (FPZ) at few selected locations. The strain pattern obtained showed development of parallel cracks with localized strain field in the fracture process zone (FPZ) near MAL, EAL locations and the first through thickness cracks in BARCOM test-model were identified successfully.

For the pre test predictions and post test ultimate load capacity evaluation of BARCOM test model, fifteen participants from Austria (1), Brasil (1), Czech Republic (1), Finland (1), France (2), South Korea (2), United Kingdom (3) and India (4) have registered. The registered round robin participants submitted the pre-test predictions at sixty-nine (69) specified sensor locations (SSL) out of total ~1100 sensors for studying BARCOM failure modes in terms of prescribed milestones, which were discussed in pre-test meeting and workshop in 2009 (Singh et al., 2009; Singh, 2009). The post-test meeting and workshop after the above mentioned over-pressure tests (OPTs) was convened in February 2011 to appraise the registered round robin participants on the test results (Singh, 2011a). There was an overall agreement on the observed failure mode of BARCOM and the participants will now carry out improved post test computations with this interim feedback for comparison of the test results. This will aid in improved understanding of the containment performance under over-pressure and help in benchmarking various numerical finite element inelastic codes.

2. BARCOM experimental program and international round robin analysis

After the completion of the civil works for the auxiliary shed, installation and commissioning of the equipments and piping system for pressurization system and MALB door fabrication and installation, the commissioning tests on BARCOM Test Model (Fig. 1) were initiated. Additional 350 surface type sensors and process parameter sensors were installed and cable routing works from the test model to the Control and Instrumentation (C&I) building and installation, commissioning and configuration of data loggers were completed in parallel to initiate the experimental program (Fig. 1). As per the plan, the model was tested pneumatically with compressed air during the low pressure tests (LPTs) followed by proof test (PT) and integrated leakage rate test (ILRT) for

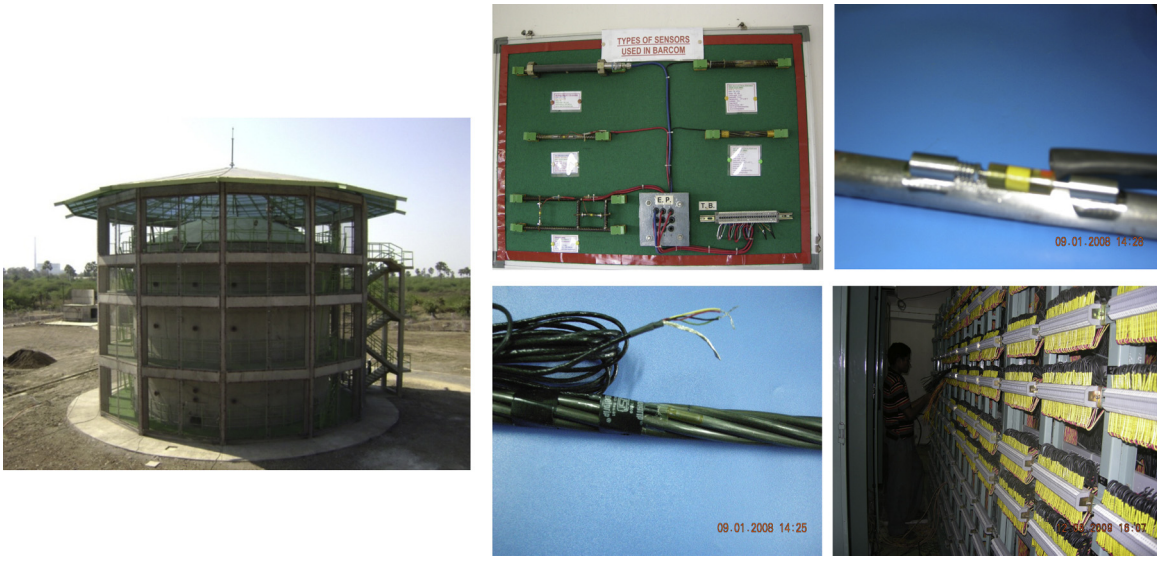

Fig. 1. BARC containment (BARCOM) test-model (Design Pressure Pd 0.1413 MPa) at BARC-Tarapur test facility with details of embedded sensors and cable panels.