Nuclear Engineering and Design 338 (2018) 247–260

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Study on mechanical behavior of containment in nuclear power plant during prestressing construction

Jiachuan Yan[a,b,*], Youzhu Lin[a,b], Wenjie Chen[d], Hongliang Qian[a,b], Tao Fang[c], Jingfang Li[d]

[a] *Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education, Harbin Institute of Technology, Harbin 150090, China*
[b] *Key Lab of Smart Prevention and Mitigation of Civil Engineering Disasters of the Ministry of Industry and Information Technology, Harbin Institute of Technology, Harbin 150090, China*
[c] *China Vanke Co., Ltd., Wenzhou 325000, China*
[d] *China State Construction Engineering Co. Ltd., Technical Center, Beijing 101300, China*

ARTICLE INFO

Keywords:
Prestressed concrete containment
Prestressing construction
Prestressed tendons
Mechanical behavior
Tensioning sequence

ABSTRACT

Taking a third generation nuclear power plant as the research background, a refined model of a prestressed concrete containment which consisted of 270 complex spatial prestressed tendons was accurately established, using FE software ABAQUS. The cooling method was adopted to simulate the tensioning process of tendons. The simulation method of the tensioning of tendons during the prestressing construction of containment was verified by comparing with the measured data on site of the practical project. The mechanical behavior of the containment during the prestressing construction according to the prestressing construction scheme on site was studied in detail. Then the influence of steel liner and reinforcement on mechanical behavior of the containment during the prestressing construction of prestressed tendons was discussed. Finally, four prestressing construction schemes were analyzed and a reasonable optimization scheme was obtained.

1. Introduction

The double-layer containment system is adopted in the third generation nuclear power plant. The outer containment is a reinforced concrete structure designed for resisting external hazards, such as aircraft crash. The inner containment is a prestressed concrete structure, consisting of a prestressed concrete dome and a prestressed concrete cylinder. The tightness of the containment can be guaranteed by inner steel liner which abuts the inner containment. The structure type of the inner containment is complex, including buttress columns, holes, ring beams and foundation. The 270 prestressed tendons are spatially distributed in the prestressed concrete dome and cylinder, which are divided into horizontal prestressed tendons, vertical prestressed tendons and Gamma prestressed tendons.

Researches on mechanical properties of containment structures under extreme loads, such as a thermal load caused by a loss of coolant accident (LOCA), seismic load, and internal pressure are sufficient. Experimental studies have been carried out to investigate the mechanical properties of the containment under the seismic load and the internal pressure. At Sandia National Laboratories, a 1:6 scale reinforced concrete containment model was tested with the increasing pressure. The failure pressure and failure mechanism of the structure were investigated (Horschel, 1988, 1992). Hirama et al. (2005a,b, 2007) carried out a series of full-scale or large scale seismic tests on a reinforced concrete containment vessel (RCCV) to validate the seismic design and reliability with a sufficient margin even under destructive earthquakes.

Rizkalla et al. (1984) tested a 1:14 scale prestressed concrete structure model of a Canadian reactor containment structure. Twidale and Crowder (1991) carried out an internal pressure test on a 1:10 scale prestressed concrete containment model of the Sizewell B containment structure. Hessheimer et al. (2003) conducted a pressure test on a 1:4 scale model of the prestressed concrete containment structure of the Ohi Nuclear Power Station Unit 3 containment structure at Sandia National Laboratories. Parmar et al. (2014) conducted the pressure tests of a 1:4 scale model of the prestressed concrete inner containment structure of Tarapur Atomic Power Station Units 3 and 4 and studied the mechanical properties of the structure under different pressures.

Based on the tests of the reinforced concrete containment and prestressed concrete containment structures, a series of numerical simulations were carried out to simulate the tests and investigate the ultimate bearing capacity for the functional failure and structural failure of

* Corresponding author at: Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education, Harbin Institute of Technology, Harbin 150090, China.

E-mail address: yanjiachuan@hit.edu.cn (J. Yan).

https://doi.org/10.1016/j.nucengdes.2018.08.022
Received 10 May 2018; Received in revised form 11 August 2018; Accepted 20 August 2018

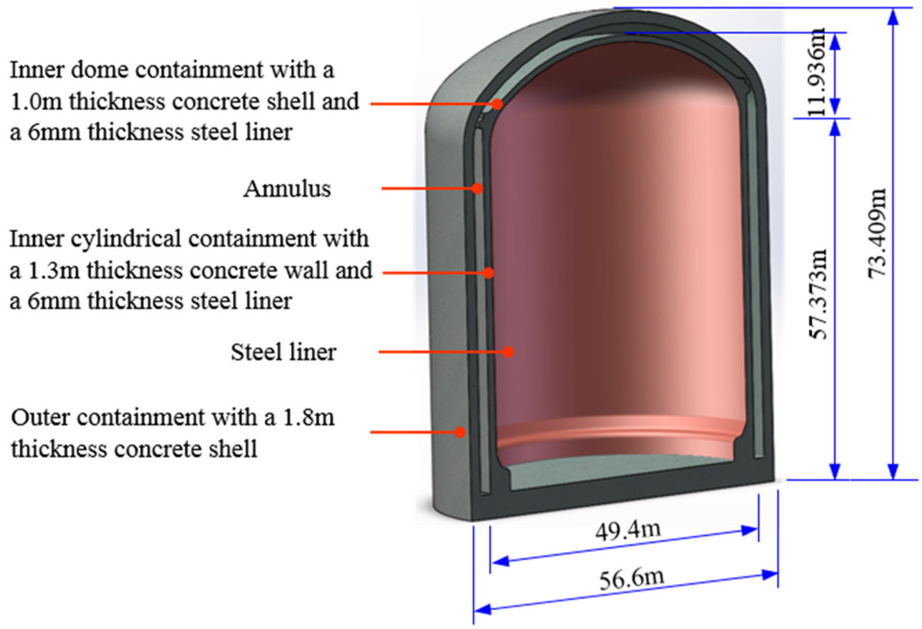

Fig. 1. Double-layer containment structure.

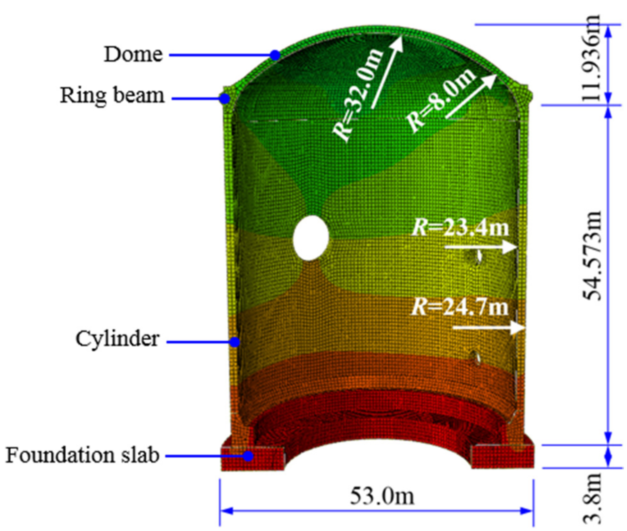

Fig. 2. Cross-section of the inner containment.

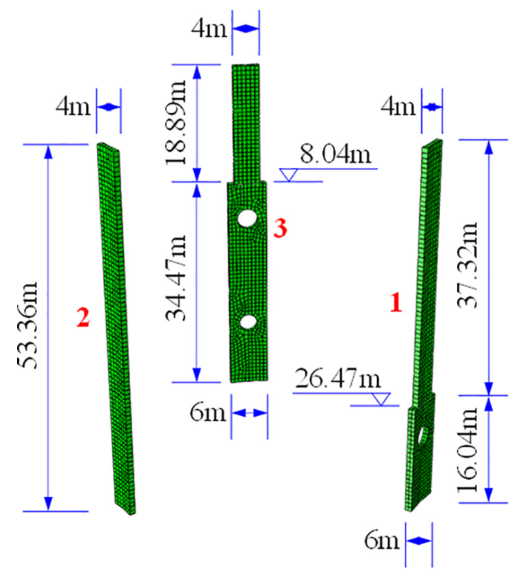

Fig. 3. Buttress columns.

the structure. Yonezawa et al. (2002) modified the friction effect between concrete and tendons, the non-liner behavior and the ultimate capacity of the structure were predicted. Lee et al. (2004) carried out the simulation by considering the tension stiffening effect to evaluate the ultimate internal pressure capacity of the structure. Kwak and Kim (2006) and Kwak and Kwon (2016) proposed two kinds of stress–strain constitutive relations of concrete and verified the effectiveness and practicability through numerical simulation analysis. Prinja et al. (2005) analyzed the 3D FE model of the containment and predicted the weak area and the failure mode of the structure. Noh et al. (2008) used an axisymmetric model and a three-dimensional model to predict the thermal and mechanical behaviors of the containment subjected to high temperature loading and internal pressure. Shokoohfar and Rahai (2016) adopted the concrete damage plasticity model to study the behavior of the structure under pressure and high temperature.

The effect of the presstress loss on the mechanical behavior has also drawn much attention from researchers. Anderson (2005) proposed models to predict the prestress loss of tendon force in containment for 30 years. Considering concrete shrinkage, creep and relaxation of prestressed tendons, Pan and Wang (2009) calculated the long term prestressing loss of prestressed tendons for post-tensioning prestressed concrete containment and Huang et al. (2017) performed the numerical simulation of the structure under service load. Dong and Zhao (2010) studied prestress loss due to friction, shrinkage and anchorage of prestressed tendons in containment for nuclear power plant. Lundqvist and Nilsson (2011) increased the accuracy of prediction models to estimate the prestress loss due to creep, shrinkage and relaxation. Hu and Lin (2016) conducted the FE analyses to estimate the ultimate pressure capacity and the failure mode of the containment considering the effect of long term prestress loss. Shokoohfar and Rahai (2017) presented a new method to compute long term prestress loss considering the interaction effect between concrete creep and tendon relaxation. Balomenos and Pandey (2017) proposed a probabilistic FE estimation to predict the prestress loss based on the relationship between the concrete strains and the prestress loss.

Bílý and Kohoutková (2015) adopted ABAQUS finite element