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Analytical evaluation of the dome-cylinder interface of nuclear concrete containment subjected to internal pressure and thermal load

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ABSTRACT

Nuclear concrete containment structures serve as the main line of defense to prevent escape of radioactive material during catastrophic events including the loss of coolant accident (LOCA), explosions and earthquake. In the case that such an event occurred, the containment would need to resist high internal pressure and temperature loads. This paper studies the dome-cylinder interface of concrete containments subjected to significant internal pressure and temperature load. In particular, the compatibility at geometry discontinuity and internal forces as a result of displacement discrepancy is investigated using nonlinear mechanics based formulas. A practical example of concrete containment is presented as a case study. The study reveals that the current practice in nuclear concrete containment design may significantly underestimate the stress at the dome-cylinder interface, which would lead to insufficient design. The presented approach provides an easy to use tool to assess the dome-cylinder interface of a concrete containment.

1. Introduction

Nuclear containments serve the critical function of providing an external protection and a leak proof boundary for containing radiation in nuclear power plants. Conventional reinforced concrete containment vessels (CCCV) are generally cylindrical structures with a hemispherical dome, while prestressed concrete containment vessels (PCCV) are cylindrical structures with either a shallow sphere torus dome or a hemisphere dome [1]. In the case of a design basis accidental scenario such as LOCA, structural integrity of containments needs to be assessed for significant internal pressure and thermal loads [2]. Furthermore, containment performance at beyond design basis accident internal pressure and temperature is also required as an input for determining the offsite consequences and accident progression of the containment during a severe accident. Following the Great East Japan earthquake in 2011, a loss of cooling at the Fukushima Dai-ichi plant led to the overheating of several reactors and the release of radioactive material, which have highlighted the need for a robust design of concrete containments [3].

Extensive research including experimental scale model testing and finite element analysis to determine behavior at accident pressure and thermal load has been performed in the last 25 years. Experimental studies include the 1/14 scale model of Gentilly-2 in Canada [4], the 1/10 scale model of Sizewell-B in the UK [5], the ¼ scale model of Ohi-3 in the US [6–9], MAEVA mock up in France [10] and 1:4 scale model of the BARC Containment test model in India [11]. Walser used both hand calculation and finite element analysis to study a pressurized water reactor (PWR) PCCV for various design load combinations [12]. Hu and Lin employed the nonlinear finite element program ABAQUS to investigate the ultimate pressure capacity and the failure mode of the PWR PCCV at Maanshan nuclear power plant [13]. Noh et. al. used the axisymmetric and three-dimensional (3D) model in order to find the effects of high temperature and pressure on PCCV [14]. Zhang et. al. evaluated the structural integrity of CPR1000 PWR containment under five typical steam explosion scenarios [15]. Zhen et al. conducted nonlinear analysis for PCCV under utmost internal pressure considering LOCA temperature [16].

However, aforementioned researches generally focus on the overall behavior of the containment. The dome-cylinder interface of a CCCV or PCCV subject to significant internal pressure and thermal loads has not yet been studied in detail, where the nonlinear structural behavior is further complicated by the geometry discontinuity. This paper studies the dome-cylinder interface of concrete containments subjected to accidental internal pressure and temperature gradient load. In particular, the compatibility at geometry discontinuity and internal forces as a result of displacement discrepancy is investigated using nonlinear mechanics based formulas. A practical example of a prestressed concrete containment (PCCV) is presented as the case study.

2. Containment shell away from geometry discontinuity

The first step is to establish mechanics solution for a reinforced

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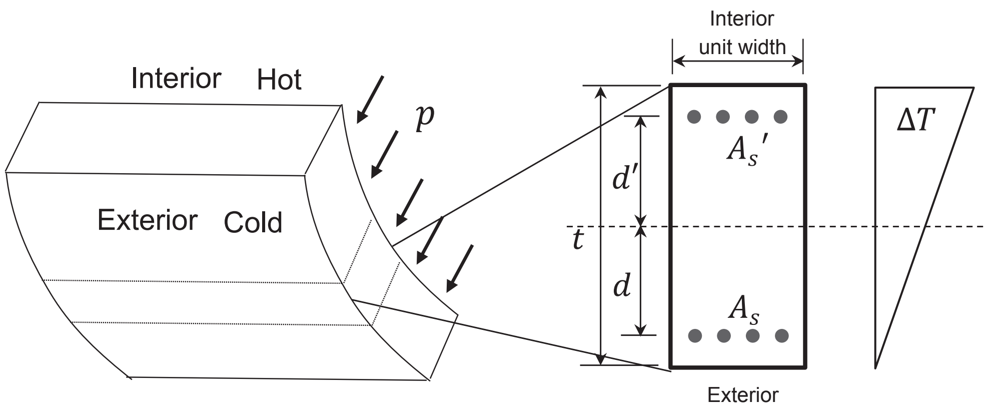

Fig. 1. Shell segment away from geometry discontinuity.

concrete shell, either within the cylindrical or dome portions of the containment. For this purpose, the formulas proposed by Wang [17] are revised and adopted in this paper. Consider a cylindrical or spherical shell segment within the concrete containment, away from geometry discontinuity such as the dome-cylinder interface as shown in Fig. 1. For a given direction of interest (either circumferential or meridional), A_s' and A_s are, respectively, areas of interior rebar and exterior rebar per unit width; d' and d are locations of interior rebar and exterior rebar measured from the centerline of the shell section; t denotes the shell thickness. Let it also be assumed that the structure is subjected to an accidental condition characterized by a linear thermal gradient ΔT and outward pressure p. In practice, a nonlinear temperature distribution may be converted to an equivalent linear thermal gradient using methods such as the one recommended by the commentary to the Appendix E of ACI 349 [18].

Combined thermal and mechanical stresses in the given direction of interest, could be calculated using the assumptions of ACI 307/ACI 349.1R [17,19–21], which are summarized as follows:

(a) The inner (hot) part is restrained from expanding freely by the outer part and the outer part is stretched by the restrained inner part.
(b) There is a neutral surface between the inner and outer parts, where the elongation due to temperature is unrestricted and therefore free of temperature stresses.
(c) Away from any geometry discontinuity, the original circular or spherical shape of the building is not altered by the temperature gradient.
(d) Horizontal sections remain horizontal after temperature changes.
(e) The tensile strength of concrete is neglected.

For a rotationally restrained section under membrane load, thermal gradients result in bending stresses. A reinforced concrete shell section with unit width is shown in Fig. 2a, subjected to a linear temperature gradient illustrated in Fig. 2b. In Fig. 2, F_s' and F_s are respectively resultant forces within exterior rebar and interior rebar per unit width; C denotes resultant force per unit width in the concrete region which remained under compression; P_c (compression as positive) represents the external membrane demand per unit width as a result of mechanical loading including internal pressure p, dead load and prestressed load if applicable.

Introduce dimensionless parameters $\lambda = 2n(A_s'd'{-}A_sd)/t^2$ and $\chi = n(A_s' + A_s)/t$ to represent reinforcement configuration of the concrete section in Fig. 2. Note that $n = E_s/E_c$ is the ratio between steel elastic modulus E_s and concrete elastic modulus E_c; χ is the total rebar ratio multiplied by modulus ratio n; λ represents the difference between $A_s'd'$ and A_sd normalized by $2n/t^2$. Using parameters λ and χ, the actual change in strain $\Delta\varepsilon$ of the shell segment can be solved for a given direction subjected to the thermal gradient ΔT and the external demand P_c as [17]:

$$\Delta\varepsilon = \left|\begin{array}{ll} \varepsilon_0\left[1 + 2\chi{-}2\sqrt{\chi^2 + \chi{-}\lambda + \frac{P_c}{E_c\varepsilon_0 t}}\,\right] & P_c > P_{c0} \\ \frac{\varepsilon_0\lambda}{\chi}{-}\frac{P_c}{E_c t\chi} & P_c \leqslant P_{c0} \end{array}\right. \tag{1}$$

In which $\varepsilon_0 = \Delta T\alpha/2$ is the fully thermal (restrained) strain while α denotes the thermal coefficient of concrete and steel (for simplicity, assume steel rebar and concrete have the same value of thermal coefficients); P_{c0} is the critical external demand of the reinforced concrete section [17] defined as $P_{c0} \equiv E_c\varepsilon_0 t[\lambda{-}\chi]$.

Subsequently for a reinforced concrete section with uniform reinforcement configuration and subjected to the thermal gradient ΔT and the external demand P_c, stresses within interior rebar σ_s', exterior rebar σ_s and maximum concrete compression stress σ_{cmax} are given by (also see Fig. 2)

$$\sigma_s' = \frac{F_s'}{A_s'} = nE_c\left(2\varepsilon_0\frac{d'}{t}{-}\Delta\varepsilon\right) \tag{2}$$

$$\sigma_s = \frac{F_s}{A_s} = nE_c\left(2\varepsilon_0\frac{d}{t} + \Delta\varepsilon\right) \tag{3}$$

$$\sigma_{cmax} = \max(\sigma_0{-}E_c\Delta\varepsilon{,}0) \tag{4}$$

Eqs. (1-4) are identical to formulas proposed by Wang [17] for thermal analysis of concrete shell. Note that those equations assume that $\sigma_{cmax} \leqslant f_c'$ and $\sigma_s \leqslant f_y$, with f_c' and f_y are concrete compression strength and rebar yield strength, respectively. In order to study a dome-cylinder interface subjected to accidental internal pressure and thermal loads, potential scenarios with concrete or steel stresses going beyond those strength limits also need to be investigated.

For concrete containments in most nuclear power plants, the maximum concrete compression stress σ_{cmax} is unlikely to exceed f_c'. For instance, consider a typical equivalent linear thermal gradient of 250F during LOCA, and use a typical concrete elastic modulus $E_c = 3605$ ksi (2.486×10^4 MPa), elastic modulus ratio $n = 8$, and thermal coefficient $\alpha = 0.0000055$/F (0.00001/C), it follows from Eqs. (1) and (4) that $\sigma_{cmax} < \sigma_0(\Delta T) = 2470$ psi, which is 60% or less compared to typical f_c' of 4000–6000 psi used in nuclear containments.

In the case that exterior rebar stress reaches yield strength $\sigma_s = f_y$ due to significant magnitudes of internal pressure and thermal gradient,

$$F_s = f_yA_s \tag{5}$$

In the context of $\sigma_s = f_y$, the exterior rebar strain $\varepsilon_s = 2\varepsilon_0 d/t + \Delta\varepsilon \geqslant f_y/E_s$. It is equivalent to:

$$\Delta\varepsilon \geqslant \frac{f_y}{E_s}{-}\frac{2\varepsilon_0 d}{t} \tag{6}$$

For typical values of $f_y = 60$ ksi and $E_s = 29{,}000$ ksi, $f_y/E_s = 0.0021$; for most cases examined in this paper, one can assume that $\varepsilon_0(\Delta T) < 0.001$ given that $\alpha = 0.0000055$/F and $\Delta T = 100$–300F. Also note that $2d/t < 1$, it follows immediately from Eq. (6), that $\Delta\varepsilon > \varepsilon_0(\Delta T)$, $P_c < P_{c0}$