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Thermal analysis of cylindrical concrete shell at transition boundary between regions with different reinforcement configurations

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ABSTRACT

Within cylindrical reinforced concrete structures, such as nuclear containments, chimneys and silos, it is common to use various hoop reinforcing ratios at different elevations, in order to optimize the design. Such structures are designed for thermal effects, generally following methods provided in ACI 307 [1], the Chimney Code or ACI 349 Code Commentary [2,3] for nuclear concrete structures. The conventional thermal analysis approach provided in aforementioned building codes is to solve the equilibrium of a given reinforced concrete section with a predetermined reinforcement configuration. However, no research has been conducted to study thermal forces and moments in transition boundary interfacing two regions with different reinforcement configurations. The compatibility at the interface between two regions with different reinforcement configurations introduces further redistribution of thermal forces and moments within the transition zone, which should be considered in the design or evaluation. In this paper, a comprehensive study has been carried out using the closed form mechanics based solution, in order to evaluate the redistribution of thermal forces and moments at the interface between two regions with different reinforcement configurations. A practical example is presented at the end of the paper to illustrate the use of the proposed method, which is then verified by using very refined finite element analysis.

1. Introduction

Primary and secondary nuclear containments serve the critical function of providing an external protection and a leak proof boundary for containing radiation in nuclear power plants. Reinforced concrete containment in a nuclear power plant typically has a cylindrical wall and a spherical dome. Within the cylindrical shell of reinforced concrete containment, it is common to use various hoop reinforcing ratios at different elevations, in order to optimize the design. From design perspective, the transition zone between regions with different reinforcement configuration represents a strength discontinuity thus needs to be evaluated properly.

During normal or abnormal operating conditions, temperature differences between the inner and outer surfaces of the cylindrical shells generate thermal stresses. The behavior of concrete structures under thermal effects has been studied for decades. In general, temperature gradients result in internal stresses due to volume changes (i.e., thermal expansion/contraction); which are reduced once the concrete is cracked. It is well known that stresses resulting from thermal effects are self-relieving and magnitudes of thermal forces and moments are directly related to the reinforcement ratio within the concrete member.

Gurfinkel [4] studied the incremental bending induced in the wall of a reinforced concrete nuclear containment by using both elastic and inelastic methods. Kar [5] presents a method for analysis of concrete members having uniform capacities along their length and subjected to a differential temperature from face to face, considering the concrete member subjected to two types of mechanical loads: (1) bending only and (2) combined bending and axial forces. Mentes [6] classify thermal analysis methods into three categories: (1) reduced flexural stiffness, (2) average flexural stiffness and (3) variable flexural stiffness. Mentes also suggested that in order to obtain a realistic evaluation of thermal moments, it is necessary to consider concrete cracking and stiffness-load interaction by an iteration process. Freskakis [7] studied behavior of a reinforced concrete section subjected to three types of thermal gradients and presented results in terms of moment–curvature–axial force relationships. Vecchio [8] proposed a sectional analysis approach to predict the response of reinforced concrete member subjected to combined thermal and mechanical loads, using iteration and layered section concept. Lee [9] performed a nonlinear finite element (FE) thermal stress analysis of a concrete waste storage using the finite element software ABAQUS and compared the

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result with ones calculated using nonlinear and linear sectional analyses.

Nuclear reinforced concrete structures., including nuclear containments, are generally designed for thermal effects following methods provided in BC-TOP-5A [10], ACI 307 [1], ACI 349 [2] and ACI 349.1R [3] and their earlier revisions. Particularly for axisymmetric shells such as a cylindrical containment, the structure is considered to be uncracked for all mechanical loads and for part of the thermal loads. The thermal load is assumed to be represented by temperatures that vary linearly through the thickness of the member, which consists of two components: (1) a uniform temperature change and (2) a thermal gradient. Normalized cracked section thermal moments are calculated as a function of the reinforcement ratio and the internal axial forces and moments acting on the section.

The general concept of approaches provided in available literatures is to solve the equilibrium of a given reinforced concrete section with a predetermined reinforcement configuration. However, no research has been conducted to study thermal stresses in transition zones between two regions with different reinforcement configurations. Conventional solutions are unable to take into account the compatibility in the transition zone, which introduces further redistribution of thermal stresses.

In this paper, a mechanics based solution has been proposed, in order to evaluate the redistribution of thermal stresses at an interface within a reinforced concrete cylindrical shell, between two regions with different reinforcement configurations. A practical example concerning cylindrical reinforced concrete containment is presented and the application of proposed mechanical formulae is validated via a very refined finite element analysis.

2. Mechanics based model for a cylindrical shell with uniform reinforcement configuration

Consider a conventional reinforced concrete cylindrical shell with uniform reinforcement configuration in hoop direction as shown in Fig. 1; A_s' and A_s are, respectively, areas of interior rebar and exterior rebar per unit height; d' and d are locations of interior rebar and exterior rebar measured from the centerline of the shell section; t and R denote, respectively, the shell thickness and radius. 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.

Thermal stresses in this cylindrical shell could be calculated using the assumptions of ACI 307 [1]/ACI 349.1R [3], which are summarized as follows:

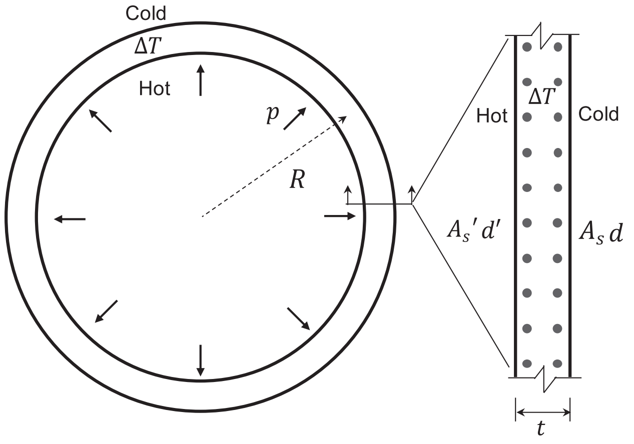

Fig. 1. Cylindrical shell with uniform reinforcement configuration.

(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) For a particular elevation, the temperature gradient through the shell thickness is the same along the building circumference. Therefore the original circular 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 height is shown in Fig. 2a, subjected to a linear temperature gradient illustrated in Fig 2b. First consider an uncracked shell section without external demand as shown in Fig. 2c, the fully restrained maximum concrete stress σ_0 is given by.

$$\sigma_0(\Delta T) = \frac{\Delta T \alpha E_c}{2} \tag{1}$$

in which α denotes the thermal coefficient of concrete and steel (for simplicity, assume steel rebar and concrete have the same value of thermal coefficients); E_c represents elastic modulus of the concrete. Because the tensile strength of concrete is ignored, thermal tensile stresses results in concrete cracking. This cracking shifts the location of the neutral axis (Fig. 2d) until equilibrium is achieved within the section (Fig. 2e), which is given by Eq. (2).

$$P_c = F_s' - F_s + C \tag{2}$$

where F_s' and F_s are respectively resultant forces within interior rebar and exterior rebar per unit height; C denotes resultant force per unit height in the concrete region which remained under compression; P_c represents the external membrane demand per unit height as a result of mechanical loading (compression as positive and tension as negative). Note that for the case shown in Fig. 1, $P_c = -pR$. Following sign convention demonstrated in Fig. 2, internal thermal forces F_s' and F_s within rebar are given by

$$F_s' = nA_s'\left(2\sigma_0(\Delta T)\frac{d'}{t} - \Delta\sigma\right) \tag{3}$$

$$F_s = nA_s\left(2\sigma_0(\Delta T)\frac{d}{t} + \Delta\sigma\right) \tag{4}$$

where $\Delta\sigma$ is the actual change in stress due to section cracking and shifting of neutral axis as illustrated in Fig 2d; $n = E_s/E_c$ is the ratio between steel elastic modulus E_s and concrete elastic modulus E_c.

For simplicity, let it also be assumed that the concrete follows a linear stress–strain curve during compression, in lieu of a parabolic one. Note that although this assumption is not always conservative, it is usually considered to be acceptable for most cases of concrete thermal analysis. The concrete resultant force C per unit height may then be calculated as

$$C = \frac{1}{2}a(\sigma_0(\Delta T) - \Delta\sigma) \tag{5}$$

where a is the depth of compression zone and is given by:

$$a = \left| \begin{array}{ll} \frac{t}{2}\,\frac{\Delta\sigma_0(\Delta T) - \Delta\sigma}{\sigma_0(\Delta T)} & \Delta\sigma < \sigma_0(\Delta T) \\ 0 & \Delta\sigma \geqslant \sigma_0(\Delta T) \end{array} \right. \tag{6}$$

Particularly in the case of $\Delta\sigma \geqslant \sigma_0$, the shell section is considered fully cracked thus no compression is taken by the concrete.