

ANALYSIS OF CONCRETE CONTAINMENTS FOR NON-LINEAR STRAIN GRADIENTS

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Summary

This paper is limited to the analysis of the effects of nonlinear strain gradients on free-standing, prestressed concrete containments. The discussed method is approximate, slightly conservative and simple. To analyze the nonlinear gradients, this method requires a computational effort similar to that for the primary mechanical loads. The effects of imposed deformation are similarly treated. The proposed method consists of four steps as explained in Chapters 3, 4 and 5. A more refined solution in the evaluation of cracking can be obtained if it is used in an iterative procedure. Finite element programs are an alternate tool to analyze the containment for these nonlinear gradients. The methods for secondary loads usually require more refinements and are more time-consuming than those used for the primary mechanical loads.

The use of layered or thick-shell finite element programs allowing progressive cracking and material nonlinearities is recommended for the final stress analysis after the containment has been designed using the proposed method.

1. Introduction

Nonlinear strain gradients are caused by secondary loading conditions, such as temperature changes and concrete shrinkage. Their resultant stresses are considerably affected by cracking of the concrete section and by creep, respectively.

This paper discusses how thin-shell programs used for the primary mechanical loads can be used to analyze the effects of the nonlinear strain gradients.

2. Nonlinear Strain Gradients

Nonlinear strain gradients across a concrete member are caused by concrete volume changes, such as temperature changes and shrinkage.

2.1 Temperature Changes

For a given time-temperature history of the containment atmosphere or for a time-radiation history due to LOCA, the transient temperature distributions can be easily determined using available computer programs. Figures 1 and 2 show typical temperature distributions across the containment wall due to LOCA. In both cases, the nonlinear strain gradients are given in terms of the temperatures. This is a convenient way to express the strain gradients because most structural analysis computer programs can include thermal analysis and imposed strain in terms of linear gradients.

2.2 Shrinkage

Shrinkage strain gradients across the wall thickness can be determined as proposed in Reference 4. Typical shrinkage strain gradients in a containment wall are shown in Figure 3. The initial zero strain condition corresponds with the strains at the end of the curing, which are assumed to be linear. Any previous strain or stress history due to temperature from the heat of hydration is ignored for simplicity.

3. The Equivalent Linear Strain Gradient (ELG)

The concept of the equivalent linear gradient (ELG) was developed by F. Baron [4] for problems involving the effects of plasticity on the behavior of structural elements subjected to axial and flexural loads (the pressure line concept). It is based on the idea that "the stress in a fiber, as given by the theory of plasticity, may be interpreted as being equal to the stress given by the elementary theory plus a correction stress to account for nonlinear stress-strain characteristics of the material." H. S. Davis [2] applied the concept to the analysis of thermal effects in the design of concrete shields. This concept can be generalized in terms of the unrestrained individual fibers or layers. Stress for each fiber or layer can be obtained from the strain compatibility across the section, the strain-stress diagrams and the assumption that plane sections remain plane before and after the nonlinear gradient is applied.

3.1 Restraints in Concrete Members

Concrete-free deformations in a structural member may be externally or internally restrained. External and internal restraints are considered independent and their effects superimposed.

Restraints external to a concrete member are those depending solely on the member boundary conditions. Once removed, the member may be considered externally unstressed.

Restraints internal to a concrete member are independent of the boundary conditions. Stresses due to internal restraints are considered in equilibrium over the cross section even when cracking is present. No boundary reactions result from the internal restraints.

3.2 Gradient Strain Components

A nonlinear strain gradient can be represented by the strain components it may produce in an externally and internally unrestrained member. The strain components are as follows:

- a. The axial strain component is the average change in length of the externally unrestrained concrete member under the nonlinear gradient (T_a in Figure 4).
- b. The curvature strain component is the rotation of the plane section produced by the gradient on the externally unrestrained concrete member. The axial and the curvature strain components can be externally restrained and, therefore, must be considered in the structural analysis (ϕ in Figure 4).
- c. The local strain component produces neither average length change nor angular change on the externally unrestrained member because they depend on the internal restraint only. The local strain component may produce cracking if the tensile strength of concrete is exceeded. It may affect the structural analysis insofar as the member stiffness is affected by cracking. However, its effect on the analysis is similar to the effect of the flexural cracking on the section stiffness (ϵ_{1c} in Figure 4).

3.3 Determination of the Equivalent Linear Gradient

For any arbitrary boundary condition and at every cross section, the ELG and the nonlinear gradient produce the same axial force (membrane force), bending moment and shear forces. The ELG can be computed by one of the following methods:

- a. Equilibrium about the plane section. As defined, the effect of the local strain component must balance or vanish [1] with respect to the plane section; therefore, the ELG must satisfy the following two conditions:

The sum of the areas between the diagram of the local strain component (ϵ_{1c}) and the ELG must vanish. The centroid of the areas between the diagram of the local strain component must coincide with the centroidal axis of the concrete gross area (CGC), that is:

$$\int_h \epsilon_{1c} dx = 0, \text{ and } \int_h \epsilon_{1c} x_c dx = 0$$

In Figure 4, Area 1 plus Area 3 must be equal to Area 2 and their moment with respect to the CGC, must vanish.

- b. With respect to an initial gradient. The ELG may be determined by finding a linear distribution of strains across the section such that:

The area between the initial gradient and the applied gradient must equal the area between the ELG and the initial gradient.

The eccentricity of both areas with respect to the CGC must be the same.

3.4 Application to Transient State Conditions

Figures 1 and 2 show only a few of the infinite temperature distributions across the containment wall during LOCA. Similarly, Figure 3 corresponds to some shrinkage strain distributions across the wall during the lifetime of the containment.

The ELG allows us to find the most critical effects produced on a section during the transient state condition as follows:

- The ELG can be determined for the transient gradients at selected time intervals and plotted as a function of time.
- Each of the ELG components will attain either a maximum or a minimum. The extreme values define the particular gradients and the components that should be considered in the analysis and design.

Figure 5 shows the variation with time of:

- a. The axial temperature component T_a . Notice the $(T_a)_{\max}$ occurs at about 15 minutes.
- b. The curvature component is given by:

$$\phi_t = \alpha (T_{ei} - T_{eo})/h$$

where T_{ei} and T_{eo} are the temperatures at the inside and outside faces of the wall from the ELG, and α is the coefficient of thermal expansion of concrete. The maximum curvature occurs at about 1 hour.

- c. The maximum local strain component $(T_e)_{\max}$ for the gradients on Figure 1 occurs at about 10 minutes. To find the $(T_e)_{\max}$ for gradients as shown in Figure 2, it may be necessary to plot the actual time-temperature history at points inside the wall corresponding to the peak values of the gradients.

4. Analysis of the Containment

A theoretically accurate analysis for a given load combination must consider the effects of cracking. However, this analysis involves iterative computations to include the variation in the stiffness of the whole structure due to cracking until cracking stabilization is obtained. The results of such an analysis are theoretically valid only for the given load combination and should not be used for any other load combination if cracking results in a structure with a different stiffness. Notice that a containment must be analyzed for at least 15 basic load combinations. Except for the permanent loads, most of the critical loads are time-dependent, which implies additional analysis work. Most structural analysis and designs are presently based on linearly elastic models using the properties of the uncracked concrete section. This assumption yields a reasonable conservatism for the mechanical loads (applied loads) because forces and bending moments from mechanical loads are not excessively affected by cracking, especially if the structure is a prestressed containment.

Assuming an uncracked section when analyzing the effects of the thermal curvature component will result in forces and moment considerably higher than those obtained when cracking is considered. In general, cracking will greatly relieve the effects of an imposed curvature when applied to a restrained structure.

The simple combination of the forces and bending moments obtained from the uncracked model may result in an overly conservative design if the effects from the mechanical loads and the thermal curvature component are combined. Conversely, an unconservative design may result if the thermal forces and moments reduce those from the mechanical loading. Cracking may eventually relieve the thermal effects below the mechanical load requirements.

A similar problem may occur with the forces and moments from imposed deformations. If a sudden imposed deformation is sustained during a long period of time (e.g., short differential settlement), or if a slow imposed deformation is applied (e.g., shrinkage strain), the induced forces and moment will be relaxed by the concrete creep.

An approximate procedure which reduces these inconsistencies and takes advantage of the thin-shell program analysis consists of the following:

- a. Determine forces and moments for each of the basic loads in a load combination.
- b. For load combinations including the effects of imposed deformation, the effects of an imposed deformation should be added to the load combination after the effects of concrete creep have been properly corrected. The age-adjusted effective modulus method is recommended as shown in References 3 and 4.
- c. For load combinations including thermal effects, consider the membrane forces, shear forces and bending moments resulting from all the mechanical loads and the axial thermal component. Also, the membrane force and shear force from the thermal curvature component should be considered, but not the moment.

The thermal curvature component will be imposed on the resultant membrane force and bending moment in the cracked section analysis as explained in Chapter 5.

5. Cracked Section Analysis

The effects of cracking and the local strain component are accounted for in the concrete cross section analysis as follows.

5.1 Curvature Component and Cracking

The thermal curvature component is imposed on the concrete cross section with an initial strain distribution. This initial strain distribution corresponds with the membrane force and bending moment from a given load combination in which the bending moment due to the curvature component is not included. It is assumed that the imposed curvature component does not cause any significant change in the membrane force. If the section is allowed to crack, the moment corresponding to the new equilibrium condition can be found as described in Reference 5. This new moment includes the effects of the mechanical loads, the thermal gradient, the reinforcement, and the cracked concrete section.

To smooth the moment transition at geometric discontinuities, the bending moment should be corrected as follows:

$$\text{when } M_t \leq M_f, M = M_i + (M_t - M_f), \quad \text{otherwise: } M = M_i$$

where:

- M_i = initial bending moment (moment from θ_t not included),
- M_t = bending moment due to the action of the thermal curvature acting on the containment,
- M_f = thermal fixed end moment,
= $EI\theta_t$ for beam elements
= $D(1 + \nu)\theta_t$ for plate or shell elements, EI and D are the elastic flexural rigidity of the beam and the plate or shell elements respectively, and
- θ_t = thermal curvature component (cracked or uncracked).

The computer program in Reference 6 was written after Reference 5. It can perform any load combination and can design the required reinforced concrete section.

Reference 6 contains further refinements of Reference 5, such as (i) using the cracked section analysis of the steel liner, and (ii) the option of imposing both the thermal axial component and the thermal curvature. In this option, the thermal membrane forces and the thermal bending moment are relaxed by cracking.

5.2 Local Strain Component

The local strain component do not usually govern the section design because:

- a. The stress-strain relationship is locally affected by the temperature, resulting in lower stresses.
- b. Stress from local shrinkage strains are relaxed by creep as shown in Reference 4.
- c. Cracking relieves the peak tensile local stresses.
- d. Compression seldom governs the design.

However, the adequacy of a concrete section can be checked using interaction diagrams for the axial force and bending moment based on the nonlinear strain distribution and the stress-strain relationship for the concrete and the steel.

6. More Refined Methods of Analysis

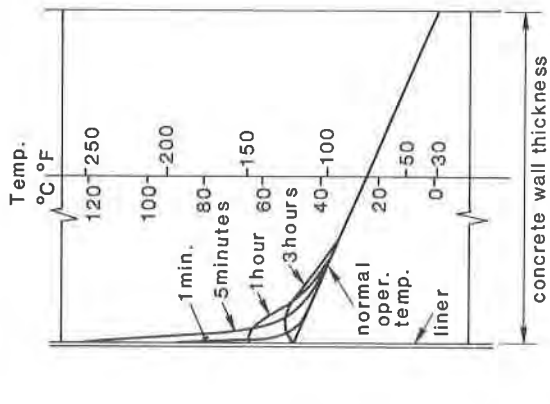
More refined methods of analysis generally involve estimating the reinforcement and the amount of cracking in an iterative process.

Numerous techniques are available in thin-shell programs to evaluate the effects of cracking. If an iterative process is used in conjunction with the proposed procedure, both the analysis and design are accomplished at the end of each cycle. Also, the effect of cracking stabilization can be assessed in terms of the designed containment.

The more sophisticated layered shell models or nonlinear thick-shell programs can be used on selected load combinations for the final stress analysis.

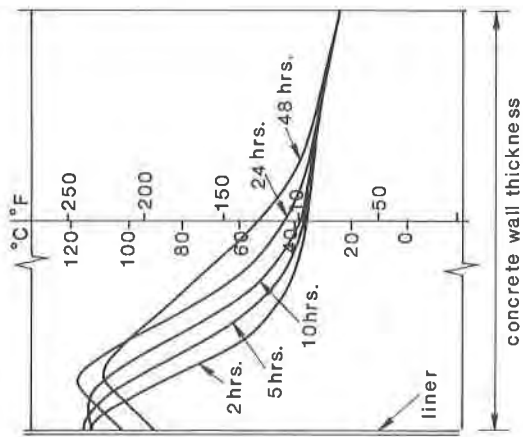
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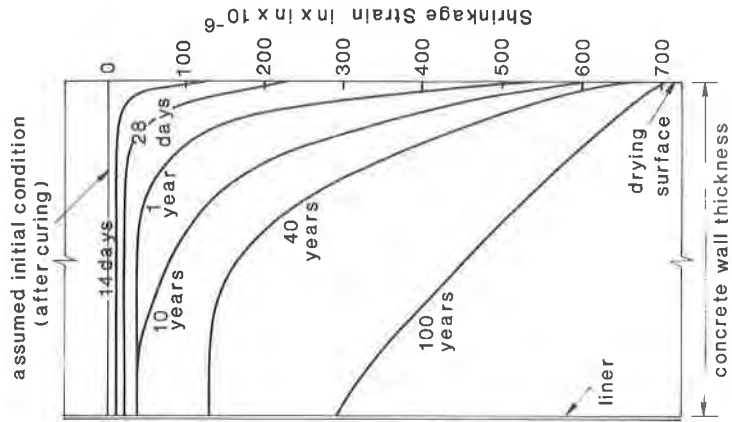
Typical temperature distributions through the containment wall due to LOCA

FIGURE 1



Typical temperature distributions due to Gamma-Ray heating subsequent to LOCA

FIGURE 2



Typical shrinkage strain gradients across the containment wall

FIGURE 3

