Nonlinear Inelastic Finite Element Thermal Stress Analysis of a Prestressed Concrete Containment Structure

M. Chatterjee, A. Unemori
Bechtel Power Corporation,
P.O. Box 3965, San Francisco, California 94119, U.S.A.
W.W.H. Chen
Research and Engineering, Bechtel National, Inc.,
P.O. Box 3965, San Francisco, California 94119, U.S.A.

SUMMARY

Nonlinear inelastic finite element thermal stress analyses of a prestressed concrete containment structure for combinations of thermal, prestress, pressure and dead loads were performed. The structure is represented using an axisymmetric finite element model in which the ductile, directionally dependent properties of the reinforcement and tendons, the limited tensile capacity of the concrete, and the ductile, isotropic behavior of the liner plate can be simulated. The complete structure, including the basemat and surrounding soil are modelled. The concrete elements are allowed to crack in tension and yield in compression. The meridionally and radially oriented rebar, hoop reinforcement, and shear ties are represented using finite elements with orthotropic stiffness and strength characteristics.

Results of the analysis indicate that for the assumptions adopted for the analysis of the structure, the effects of cracking and reinforcement are critical to the predicted structural behavior. With the exception of the load combination corresponding to the structural integrity test, each of the prescribed load combinations induced some degree of inelastic behavior at certain locations in the structure. However, although cracking is predicted in five of the six load cases examined, the integrity of the structure is believed to be uncompromised for the following reasons:

(1) An extremely conservative value of concrete tensile capacity was adopted,

(2) None of the rebars yielded. The maximum rebar stress observed was 45% of the prescribed yield stress, and

(3) In no case were the induced concrete stresses more than 85% of the prescribed ultimate compressive strength.

1. Introduction

Analysis of a prestressed concrete containment structure is required to examine the structural adequacy of the final design for a variety of prescribed loads and load combinations as well as to predict a priori such parameters as displacements induced during the structural integrity test (SIT). The necessary analysis is often performed by employing linear elastic behavior assumptions, which fail to simulate the effect of concrete cracking and the orientation and yielding of the steel reinforcement. This paper describes the nonlinear inealstic finite element thermal stress analysis of a prestressed concrete containment structure for each of several prescribed loading combinations of thermal, pressure, prestress and dead loads.

The analyses were performed using a two-dimensional, static, small displacement bilinear inelastic finite element thermal stress analysis computer program which was developed to perform plane strain, plan stress, or axisymmetric stress analysis of reinforced concrete structures. In particular, the program can simulate the effects of both cracking of concrete and the yielding of steel reinforcement in structures subjected to thermal and other static loads. As will become evident later, these effects are critical to the predicted behavior of the structure.

2. Analytical Assumptions

The results of the analysis presented in this paper are based on several significant analytical assumptions. First and most important, it is assumed that the nonlinear transient thermal stress response of the containment structure can be simualted to a reasonable degree of accuracy by statically analyzing the structure for a series of load combinations which include three different thermal gradients. These gradients include the steady-state gradient and two instantaneous thermal gradients (at 1 hr and 24 hrs) calculated for the structure using transient heat transfer analysis. Procedurally, independent thermal stress analysis are performed for each of these thermal gradients in combination with the other static loads.

Second, the structure is modelled as an axisymmetric structure in spite of the fact that only the Prestressed Concrete Containment Vessel (PCCV) wall is axisymmetric. In a similar vein, the reinforcement and tendons in the top of the dome are idealized as being oriented either meridionally or circumferentially when, in reality, practical considerations dictate that an orthogonal grid be employed.

Finally, the numerical algorithm implemented the computer code assumes that the state of stress which exists when the converged solution is achieved is independent of the stress history of the loading. That is, the nonlinear solution algorithm is path-independent. This assumption is a reasonable one when compared to the degree of accuracy which inherently exists in such factors as (1) the extent of cracking in the structure due to shrinkage, construction loads, or foundation settlements prior to the application of the prescribed thermal and pressure loads, (2) the magnitude and distribution of presstressing loads, or (3) the tensile capacity of the concrete used in the analysis.

3. Analysis Model

The program selected for use in the analysis was developed primarily to perform non-linear, inelastic, static analysis of axisymmetric reinforced concrete structures. As a consequence, the ductile, directionally dependent behavior of the reinforcement and tendons, the brittle behaviour of the concrete, and the ductile, isotropic behavior of the liner can be simulated. In order to take full advantage of these features, an axisymmetric model of the containment structure with 1032 nodes and a total of 1530 elements with seven (7) different material properties was developed.

The program can consider two types of materials, ductile and brittle. For ductile materials, it uses the total displacement theory of plasticity (i.e., $E_{ffective}$ is used for stressed greater than the yield stress (Figure 1). For Brittle materials, it uses a maximum principle stress fracture theory (Figure 2). After an element has cracked, the extensional modules, E, is replaced by E_{crack} in the cracked direction.

Material 1 is used to simulate the high strength concrete elements used in the PCCV and the portion of the basemat just above the tendon gallery. The concrete elements are allowed to crack in tension and yield in compression. The tensile strength of concrete was assumed to be equal to 3% of the compressive strength of the concrete. Yield stress was assumed to be 2/3 of the ultimate compressive strength of the concrete.

The meridionally and radially oriented rebars including hoop reinforcement and shear ties are simulated by Material 2. The reinforcement elements are allowed to yield in both compression and tension. For each of these elements, a fill ratio is specified for the corresponding orientation of rebars in accordance with the following expression:

$$\text{Fill Ratio} = \frac{\text{Total volume of reinforcing bars}}{\text{Total volume of concrete}}$$

The steel liner plate element is represented by Material 3. Material 4 simulate the meridional and hoop prestressing tendons. As in the case of the rebars, the action of the prestressing tendons is simulated by specifying the calculated corresponding fill ratios. The following assumptions were made in modelling the tendon properties:

1. Tendons remain effective after prestress is overcome,

2. Yield stress of tendons is adjusted for the average prestress and average compressive stress resulting from the mathematical modelling of the prestress effect on the PCCV, and

3. The yield stress is not adjusted for effect of the dead weight of the PCCV.

The lower strength concrete elements in the basemat are simulated by Materials 5 and 7. Material 7 differs from Material 5 only in that the tangential stiffness of Material 7 is assumed to be zero. As was the case for the high strength concrete (Material 1), the basemat concrete is allowed to crack in tension and yield in compression. Tensile strength is set equal to 3% of the ultimate compressive strength of the material. The soil elements are represented by Material 6.

4. Loads and Load Combinations

4.1 Loads

The loads considered in the analysis included dead load (D), prestressing loads (Fo and Fe), accident pressure loads (P2), and thermal loads (T1W and T2W). The dead load consists of the weights of the PCCV wall, PCCV dome, primary shield, secondary shield, reactor external building walls, and basemat. The unit weights of concrete and steel are 2.40 t/m^3 and 7.85 t/m^3, respectively.

Prestressing of the PCCV is achieved by a post-tensioning system which uses groups of 163 - 7 mm tendon wires. The magnitude of the prestres loads of the tendons at various positions in the containment shell at the time of testing (Fo) and at the end of 40 years (Fe) are used.

The maximum internal pressure acting on the containment one hour after LOCA is 4.0 kg/cm^2. Internal pressure acting on the containment 1 day after the LOCA is 0.64 kg/cm^2. These accident pressure loads should be evaluated with the corresponding thermal effect. Maximum external pressure acting on the containment is 0.0 kg/cm^2. Temperature gradients in the PCCV following a postulated Loss of Coolant Accident (LOCA) can result in considerable thermal stresses. To obtain the maximum thermal gradient, each load case is analyzed under winter conditions of 42°C air inside and 1.2°C outside the containment prior to the time of LOCA initiation. The temperature at the bottom of the basemat is 16°C. Three design thermal gradients (steady state conditions (T1W) prior to the LOCA, at one hour (T2W - 1 hr) and one day (T2W - 24 hr) post-LOCA were used in the analysis. These thermal gradients following a LOCA were determined using transient heat transfer analysis.

4.2 Load Combinations

The six load cases considered in the analysis are as follows:

LOAD CASE	LOAD COMBINATION	LINER
1	D + Fe + P2(1HR) + T2W(1HR)	L
2	D + Fe + 1.5 P2(1HR) + T2W(1HR)	L
3	D + Fe + P2(1HR) + T2W(1HR)	NL
4	D + Fo + 1.15 P2(1HR)	L
5	D + Fe + T1W(STEADY STATE)	L
6	D + Fe + P2(24HR) + T2W(24HR)	L

5. Analysis Results

With the exception of the load combination corresponding to the structural integrity test [Load Case 4, D+Fo+1.15 P2(1 HR)], each of the prescribed load combinations induced some degree of inelastic behavior at certain locations in the structure. Since the solution algorithm used in an iterative one, the onset of inelastic behavior dictates that several cycles of iteration be performed in order to achieve a converge solution. It was observed that a converged solution was obtained in each case.

Figure 3 identifies the reinforced concrete elemtns in which cracking can be expected for load case 6. The cracks shown are catagorized with respect to the orientation of the predicted crack plane. The extent and nature of the cracking shown in these figures may be somewhat overestimated and misleading, respectively, for a number of reasons. First, a conservative estimate for the tensile strength of concrete was used in the analysis. To be specific, a tensile capacity equal to 3% of the compressive strength of concrete was employed in the analysis although higher values of tensile capacity ranging from 9% to 16% of the compressive strength of concrete have been observed (Reference 1). Second, in reality, the action of steel reinforcement is not developed until cracks form in the concrete. From an ultimate strength design standpoint, then, the amount of steel required to reduce rebar stresses to acceptable levels is much more important than the onset of cracking. In fact, for the 6 load cases evaluated, none of the rebars in the containment structure yielded.

With respect to the displacements, Load Case 2 [D+Fe+1.5 P2(1 HR) + T2W(1 HR)] induces the largest stresses at selected locations. This is consistent with expectations since Load Case 2 combines the most severe thermal gradient (1 HR winter accident) and pressure loadings required for design.

In terms of the concrete stresses at the prescribed locations, a maximum compressive stress of 279 kg/cm^2 occurs in the PCCV in Load Case 6 [D+Fe +P2(24 HR)+T2W(24HR)]. This value of compressive stress compares with a value for compressive yield stress equal to 280 kg/cm^2, and a value for the ultimate strength of the PCCV concrete equal to 420 kg/cm^2. In fact, in the PCCV, only in Load Case 3 [D+Fe+P2(1 HR)+T2W(1 HR) - no liner] were two concrete elements stressed beyond yielding. Further, maximum compressive stress in these elements (281 kg/cm^2) exceeded the prescribed yield stress by less than 0.6%.

With respect to rebar stresses, Load Case 2 [D+Fe+1.5 P2(1 HR) + T2W(1 HR)] induces the largest stresses at the selected locations. Again, this is consistent with the observation that Load Case 2 combines the maximum thermal and pressure loads on the PCCV. Equally important, the value of the maximum rebar stress at selected locations for Load Case 2 is equal to 1712 kg/cm^2, which is les than 43% of the prescribed rebar yield stress (4000 kg/cm^2). Indeed, the maximum rebar stress in each of the load cases (1789 kg/cm^2) is less than 45% of the rebar yield stress.

6. Summary and Conclusions

In summary, the results of the analysis indicate that the design of the prestressed concrete containment structure is adequate for all of the load combinations considered. Although cracking is predicted in five of the six load cases, the integrity of the structure is believed to be uncompromized for the followinng reasons:

(1) An extremely conservative value of concrete tensile capacity was adopted,

(2) None of the rebars are expected to yield. The maximum rebar stress observed was 45% of the prescribed yield stress, and

(3) In no case were the induced concrete stresses more than 85% of the ultimate compressive strength of the concrete to be used in the structure.

REFERENCE

Bresler, B., REINFORCED CONCRETE ENGINEERING, Chapter, 3 John Wiley and Sons, New York, New York, 1974.

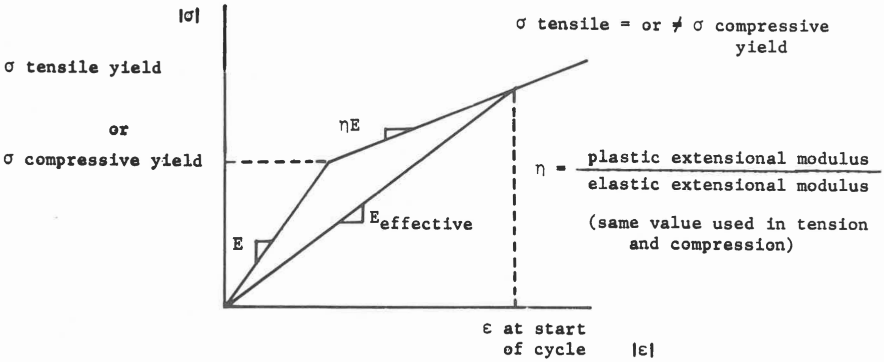

Figure 1 Uniaxial Stress Strain Curve For Ductile Material

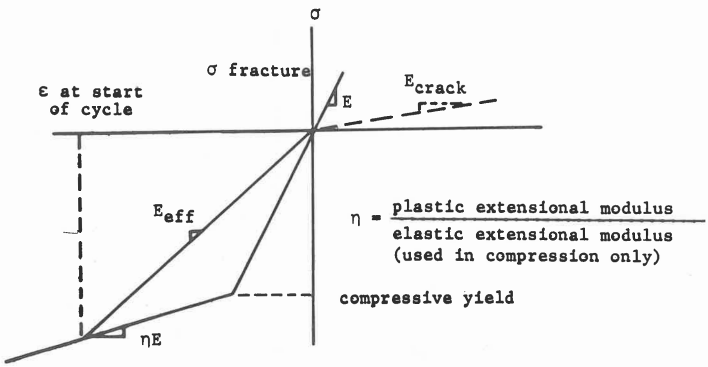

Figure 2 Uniaxial Stress Strain Curve For Brittle Material

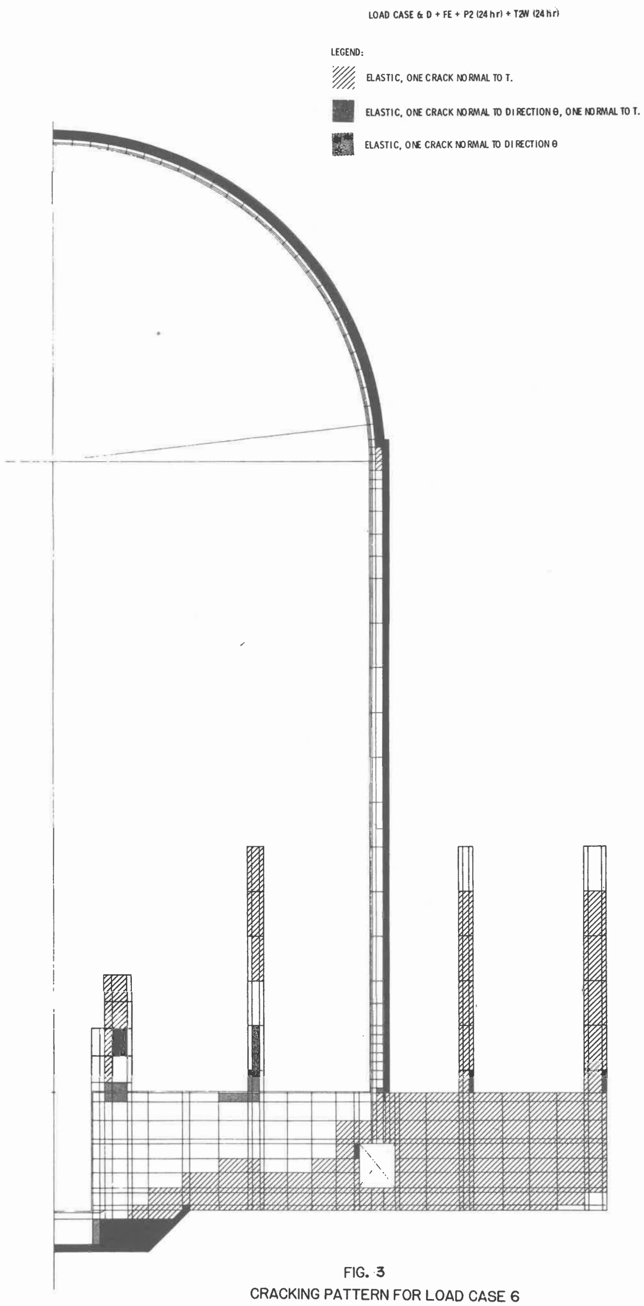

FIG. 3
CRACKING PATTERN FOR LOAD CASE 6