ANALYSIS OF PRESTRESSED CONCRETE REACTOR VESSELS UNDER HIGH THERMAL GRADIENT

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SUMMARY

Gas cooled nuclear reactors often require a large core space for which prestressed concrete reactor vessels have been adopted. These vessels are currently being designed as radially and transversely prestressed cylinders capped with flat end slabs or hemispherical heads, or as spherical shells.

The state of stress in a vessel subjected to prestressing forces in two orthogonal directions and internal pressure in addition to sharp thermal gradients is a complex one. A discrete parameter approach in which material properties are recognized in detail offers a rational method of attack. In this paper, a finite element solution is presented for cylindrical vessels with flat end slabs. The effect of introducing cracks of arbitrary orientation at the cylinder-slab junction is investigated. Although the analysis is made for linearly elastic materials, it is shown that cracking at the reentrant corner affects the distribution of radial displacements on the inside face of the end slab, and increases tensile strains on the outside face of the end slab. The effect of temperature variation through the thickness is investigated for a given state of initial stresses.

Results obtained from the analysis are next compared with those given by S.L. Paul et al. (University of Illinois, Structural Research Series No. 346, Urbana, July 1969). Although experimental results are for the entire range of loading, from "elastic" behavior to ultimate, and do not include thermal influences, good agreement is obtained for the initial stages. It is concluded that thick axisymmetric shell elements can be employed with good accuracy in the structural analysis of vessels of the type considered.

1. Introduction

Gas cooled nuclear reactors call for a large core volume which in turn requires the construction of large primary containers. To meet the general requirements that these vessels be easy to construct and to transport has led to the adoption of prestressed concrete reactor vessels (PCRV's) which serve to hold the cooling system and provide the required shielding with the added advantage of being constructed on site {1} .

In the design of PCRV's, the fundamental principles implemented for prestressed beams and slabs are employed. Concrete and the prestressing tendons are the main structural elements of a PCRV. The load carrying elements are primarily the prestressing tendons to which pressure loads are transmitted by the concrete. The concrete walls provide the necessary shielding and some temperature isolation. The basic idea is to precompres the walls of the vessel to such a level that as the internal pressure is increased to the operating level, concrete will remain dominantly in compression, resulting in an essentially stress-free container. This has been referred to as the "pressure balance concept" {2} .

The PCRV is basically an internal pressure resisting structure and as such the most efficient shapes would appear to be spherical or cylindrical or a combination of these {3} . For ease of construction and analysis, the thick walled cylinder capped either by a spherical dome or a flat slab has been preferred. Design is usually satisfied by an elastic analysis of the structure since it is desirable that the vessel remain "elastic" when subjected to operational and sometimes seismic loadings.

The structural analysis of prestressed concrete reactor vessels have been carried out by using finite element codes of varying complexity. This line of attack allows the determination of the state of stress around openings and can further take into account the effects of creep and shrinkage. Inelastic discrete studies have also been carried out to investigate the behavior of vessels near ultimate {1,4}. Experimental correlation of the results of these analyses have been made {5,6,7,8} but generally speaking information on the behavior of scaled vessel models of different configuration is not extensive.

The temperature gradients that develop in the boundaries of the vessels are a very important phase in the design process. In spite of the extensive thermal insulation on the inside face of vessels, sharp gradients are likely to be developed which affects the distribution and magnitude of stresses significantly.

The object of this report is twofold : first, the effect of circumferential cracking at the reentrant corner of cylindrical vessel delimited by a thick slab will be investigated. The model structure, identical in shape and size to one of the vessels reported in Ref. {5}, is shown in Fig.1. The development of a crack of the postulated type generally forewarns of a flexural failure in the end slab, although for thicker end slabs the "shear" type of failure would be more likely {6}. Second, the effect of a sharp temperature difference between the inside and outside faces of the vessel will be studied with reference to steady state conditions.

2. The Structural Analysis

The axisymmetric PCRV shown in Fig.1 and subjected to the uniform action of the prestressing tendons and internal gas pressure was analyzed as an axisymmetric linearly elastic solid. No discontinuities in the elastic medium other than circumferential cracking at the reentrant corner will be considered.

The finite element used in the analysis consists of a four-node general quadrilateral with improved bending capability {9}. The mesh arrangement as well as the dimensions of the axisymmetric solid are indicated in Fig.2. As reported in Ref. {5}, this particular structural model did not contain bonded reinforcement. The longitudinal reinforcement was provided by 30 strands placed symmetrically and each tensioned to 11,300 kgf. Circumferential prestress was applied by means of 0.49 cm diameter wire at a spacing of 0.85 cm and stressed to 1,860 kgf. This hoop prestress is equivalent to a radial external pressure of approximately 35.0 kgf/cm^2.

Both longitudinal and hoop forces will increase when internal pressure is applied and outward displacements take place. This increase is likely to be small, however, for the range of displacements to be considered, and will not be taken into account.

The elastic modulus for the 500 kgf/cm^2 concrete was taken as 300,000 kgf/cm^2 with Poisson's ratio equal to 0.17.

It has been reported {5} that the first crack to form in the vessel as internal pressure was increased was a circumferential crack at the reentrant corner. This occurred at an internal pressure of about 35.0 kgf/cm^2. From this point on, as the internal pressure was increased, new cracks formed in succession which were primarily radial cracks starting near the center of the slab. The formation of the circumferential crack, then, can be viewed as the beginning of the transition from elastic to inelastic behavior. The extent of this crack will have a strong influence on the distribution of stresses in the later stages of loading. In Fig.2, the thick line drawn at 45 degrees in the reentrant corner depicts three different stages of cracking:the location of the symbol 0 indicates no cracking, and the symbols 1 and 2 show two different penetrations of the crack. The influence these three different penetrations on the vertical displacement of the end slab and the radial stress variation near the inside and outside faces of the end slab are shown in Fig.3. The internal pressure for all cases is taken as 35.0 kgf/cm^2. The vertical displacements shown in Fig.3a are measured from the unstressed state of the vessel, that is before the application of prestressing forces. The presence of cracking produces stress differences on both the outside and the inside faces of the end slab of the order of 10 to 12 percent. The actual difference is likely to be higher, however, due to additional cracks forming along the radial direction on the axes of symmetry.

In order to provide experimental verification of the analysis a comparison was made between measured and calculated strains on the inside face of the end slab. For consistency, radial and circumferential strains measured at the radial distances of 9.5 and 35.5 cm. were selected for model PV9 {5}. Figure 4 summarizes this comparison. It is seen that the assumption as to the extent of cracking causes differences of strain magnitudes of about the same order as the spread of the experimental values. In particular, correlation is good for radial strains at 35.5 cm. radius and generally within acceptable limits for the remaining cases.

3. Thermal Analysis

Stresses and displacements computed with consideration of prestress forces and internal pressure only will give an imcomplete picture for a reactor vessel. During the normal operation of the vessel additional stresses and deformations due to temperature effects will completely alter the state of stress. To obtain a quantitative assessment of this change, an analysis based on the uncoupled thermoelastic theory was made. The steady state heat conduction problem was solved {10} for the region indicated in Fig.2 using the same finite element mesh arrangement with the temperature boundary conditions of $100^{o}C$ on the inside and $0^{o}C$ on the outside together with zero flux conditions on the symmetry axes. The temperature boundary conditions chosen represent a rather steep gradient through the vessel thickness but is not entirely unrealistic if one considers the design values assumed for actual reactors {2}. After the determination of the temperatures throughout the axisymmetric region, an elastic analysis was carried out under the combined effects of temperature, internal pressure and prestress forces.

Figure 5 gives insight into the order of magnitude of stress differences that may be expected when thermal effects are taken into consideration. In this figure, the distribution of the radial stress along the inside and outside faces of the end slab is shown. Solid lines depict the state of stress for the case when internal pressure and prestress alone are present while the broken lines indicate the effect of temperature. No cracking was considered in the solution. It is likely for this particular example that if there had been a temperature difference of the indicated magnitude, local crusting of the concrete on the inside would have occurred. Also, unless adequate bonded reinforcement or cross-prestressing on the end slab is provided, radial cracking on the outside face would be indicated.

4. Conclusions

This paper has reviewed the effects of cracking at the slab-wall junction of a cylindrical PCRV capped by a thick end slab and the added effect of a sharp temperature gradient. Limited circumferential cracking appears to cause variations in stress which are tolerable within an ordinary design process. The temperature gradient, on the other hand, has a strong influence on stress distribution, and an accurate evaluation of this effect is of paramount importance.

References

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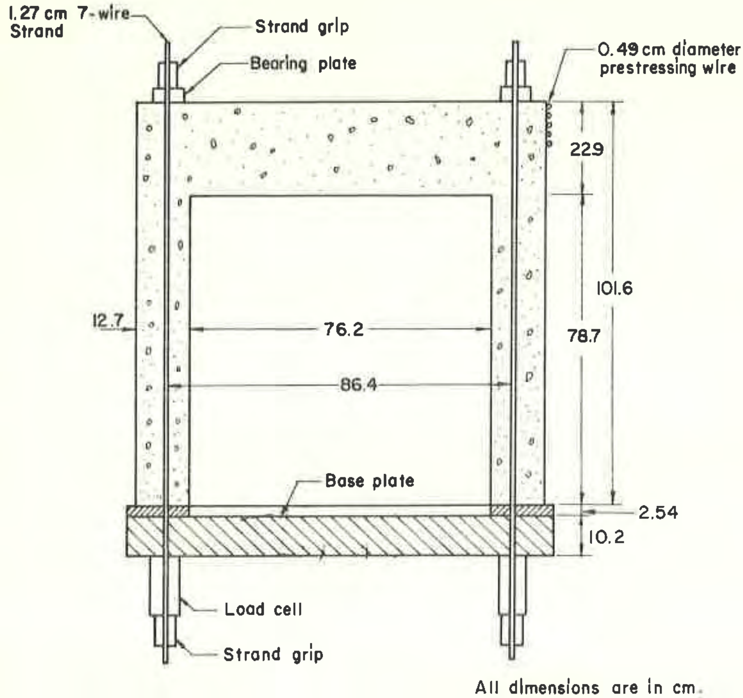

Fig. 1 - The Model Prestressed Concrete Reactor Vessel (Ref. 5)

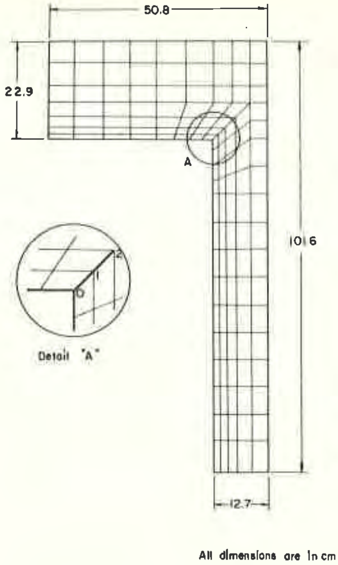

Fig. 2 - Axisymmetric Solid Model With Crack Penetrations and Mesh Arrangement

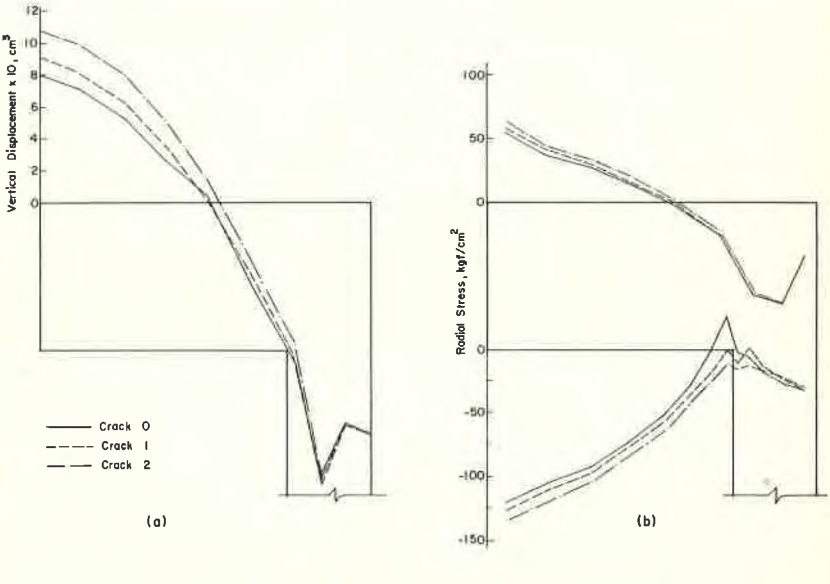

Fig. 3 - Influence of Crack Penetration on Slab Displacement and Radial Stress

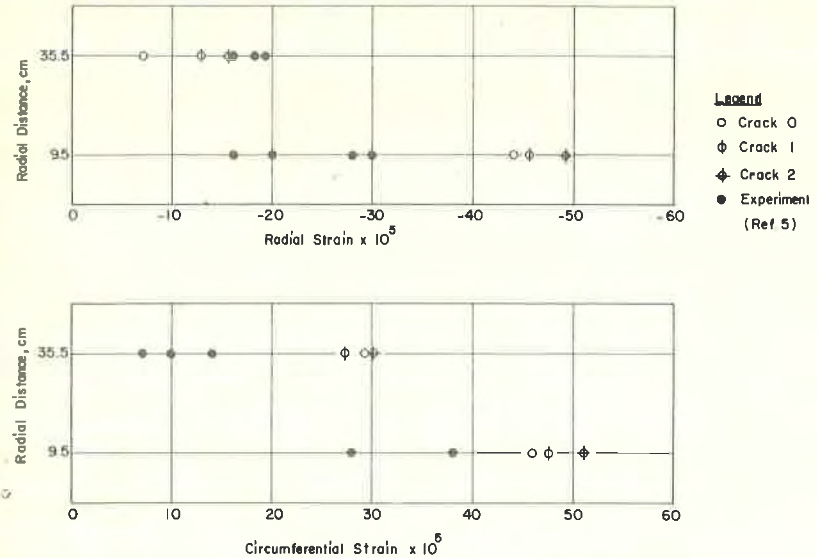

Fig. 4 - Comparison of Measured and Calculated Strains, Inside of End Slab

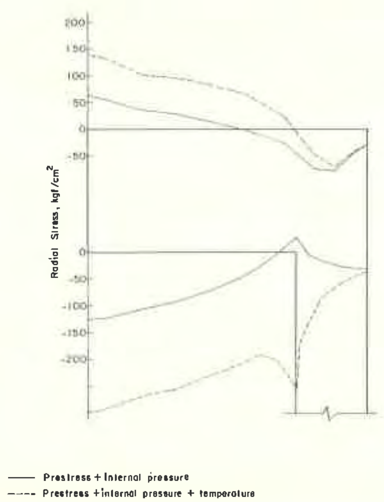

Fig 5 - Influence of Temperature on Radial Stress Distribution in the Outside and Inside Faces of End Slab