The simulation of endochronic model in the cracking analysis of PCPV

Y.Bangash
Faculty of Engineering and Applied Science, Middlesex Polytechnic, Enfield, UK

1. INTRODUCTION

The paper gives initially general steps of flow cum-crack analysis using three dimensional finite element. Endochronic model is used in which a provision is made for the increment of inelastic dilatancy, variable, shear and bulk moduli. A set of material parameters obtained by fitting numerous test-data is used for the non linear analysis of PCPV. The endochronic model is then extended and is linked to a cracking analysis within the global finite element program ISOPAR. The Oldbury Vessel parameters are used to test the analysis. Certain analytical results such as deflections are compared with those of the first seven years of the operational or monitoring techniques of the Oldbury Vessel.

2. CONSTITUTIVE RELATIONS FOR ENDOCHRONIC MODEL

An extensive work has been carried out by Bazant and Bhat (1976) on the basic incremental constitutive equations.

$$(1)\qquad (dS_{ij} + \delta_{ij}\, d\sigma_m) + (dS^P_{ij} + \delta_{ij}\, d\sigma_m)$$

$$= 2Gd\varepsilon_{ij} + 3Kd\varepsilon_m\delta_{ij}$$

The strain increment $d\varepsilon_{ij}$ is defined as in terms of instrinsic time increment

$$(2)\qquad dz = {}^{d\eta}/{z_1 F_2}\left[1 + \frac{\beta_1\eta + \beta_2\eta^2}{1 + F_1 a_7}\right]$$

where η_1 z_1 β_1 β_2 and a_7 are coefficients

(3) The volumetric strain incrementis $d\varepsilon_m = \dfrac{d\sigma_m}{3K} + d\lambda$

The shear and bulk moduli are assumed to be dependent on the inelastic dilatancy λ such that

$$(4)\qquad \lambda = \Sigma d\lambda$$

The incremental stresses are computed for up to plastic conditions as

$$(5) \quad d\sigma_{ij} + d\sigma_{ij}^{P} = 2Gd\varepsilon_{ij} + (3K - 2G)\delta_{ij}d\varepsilon_{m}$$

The stress strain relation in a matrix form is given as

$$(6) \quad \begin{Bmatrix} \Delta\sigma_x + \Delta\sigma_x^{P} \\ \Delta\sigma_y + \Delta\sigma_y^{P} \\ \Delta\sigma_z + \Delta\sigma_z^{P} \\ \Delta\tau_{xy} + \Delta\tau_{xy}^{P} \\ \Delta\tau_{yz} + \Delta\tau_{yz}^{P} \\ \Delta\tau_{zx} + \Delta\tau_{zx}^{P} \end{Bmatrix} = \begin{bmatrix} (K + \frac{4}{3}G) & (K - \frac{2G}{3}) & (K - \frac{2G}{3}) & 0 & 0 & 0 \\ & (K + \frac{4}{3}G) & (K - \frac{2}{3}G) & 0 & 0 & 0 \\ & & (K + \frac{4}{3}G) & 0 & 0 & 0 \\ & & & \beta' G & 0 & 0 \\ & & & & \beta' G & 0 \\ & & & & & \beta' G \end{bmatrix} \begin{Bmatrix} \Delta\varepsilon_x \\ \Delta\varepsilon_y \\ \Delta\varepsilon_z \\ \Delta\gamma_{xy} \\ \Delta\gamma_{yz} \\ \Delta\gamma_{zx} \end{Bmatrix}$$

(6a) Where $\{\Delta\sigma_p\} = S_{ij}\ dZ + \delta_{ij}\ 3K\ d\lambda$

A departure from the original concept is based upon the introduction of the concrete aggregate interlocking effect β' which varies from 1 to 0.5.

When concrete cracks, a sudden drop of tensile strength across the crack is assumed to occur. This creates a non-equilibrium state in the vessel. To maintain an equilibrium state, this released stress is redistributed to another part of the vessel. The material matrix, $[D_T]$, is then modified to reflect the reduced stiffness across the crack. The above material constitutive relations in the crack coordinate system is then given as (Ref. Eq.(6)).

$$(7) \qquad \underset{\sim}{\Delta\sigma^*} + \underset{\sim}{\Delta\sigma}^{P*} = \underset{\sim}{D_T^*}\cdot\underset{\sim}{\Delta\varepsilon^*}$$

Where one crack normal to X* direction occurs, then concrete is assumed to resist no longer any tensile stress in that direction, hence

$$(8) \qquad \Delta\sigma_x^* = 0$$

$$D_{11} = \Delta\varepsilon_x^* + D_{12}\Delta\varepsilon_y^* + D_{13}\Delta\varepsilon_z^* = \Delta\sigma_x^{P*}$$

$$\Delta\varepsilon_x^* = \Delta\sigma_x^{P*}/D_{11} - D_{12}/D_{11}\ \Delta\varepsilon_y^* - D_{13}/D_{11}\ \Delta\varepsilon_y^*$$

Upon substituting Equation (8) with the second and third row of Equation (7) and rearranging the terms in D_T^*; the following is obtained:

$$(9) \quad \Delta\sigma_y^* + \Delta\sigma_y^{P*} - D_{12}/D_{11}\,\Delta\sigma_x^{P*} = (D_{22} - \frac{D_{21}D_{12}}{D_{11}})\,\Delta\varepsilon_y^* + (D_{23} - \frac{D_{12}D_{13}}{D_{11}})\,\Delta\varepsilon_z^*$$

$$\Delta\sigma_z + \Delta\sigma_z^{P*} - D_{13}/D_{11}\,\Delta\sigma_x^{P*} = (D_{23} - \frac{D_{12}D_{13}}{D_{11}})\,\Delta\varepsilon_y^* + (D_{33} - \frac{D_{13}D_{31}}{D_{11}})\,\Delta\varepsilon_z^*$$

$$\Delta\tau_{xy} + \Delta\tau_{xy}^{P*} = \beta D_{44}\gamma_{xy}^*; \quad \Delta\tau_{yz}^* + \Delta\tau_{yz}^{P*} = D_{55}\Delta\gamma_{yz}^*;$$

$$\Delta\tau_{zx}^* + \Delta\tau_{zx}^{P*} = \beta D_{66}\Delta\gamma_{zx}$$

Equation (9) is referred to a local (crack) coordinate system. It is then transformed in the global coordinate system.

It there are two cracks at one point (let it be X* and Y*) and both cracks are open, then the D_T^* matrix is modified using the same principle as described above, except that in this case a double condensation is needed. For all three cracks open, the concrete loses its stiffness and D_T^* is given by:

$$[D_T^*] = 0$$

3. APPLICATION TO PCPV

The Oldbury Vessel parameters are chosen. The helical cables of 22 layers (160 cables/layer) are placed clockwise and anti-clockwise. A 45 degree helix forms a barrel shape structure. In the cap the horizontal prestressing consists of 30 cables per layer (total 20 layers) pass through the network of helical cables. The cables are anchored in four galleries. External loads due to these cables are computed and are applied at appropriate levels. A typical 3D 20 noded ISO-parametric finite element is chosen for the vessel concrete with 3D line and membrane elements for prestressing cables and liner. The effect of liner anchorage is ignored. A typical finite element mesh is shown in Figure 1.

The vessel was analysed for the design pressure, temperature, creep and prestressing loads (operational condition for a period of 7 years). Typical stresses in the circumferential directions are shown in Fig. The analysis is then adjusted to be in line with the test pressures considered by Brown et al (1975). Figures 3 and 4 show a comparative study of deflections for the barrel wall and the top cap.

For the ultimate loading conditions, in addition to the normal operational loads of the vessel, the pressure in all cavities of the vessel is increased monotonically until failure occurs. The internal pressure to the point of failure of vessel is applied in 12 increments. The first increment is slightly above the normal operational condition loads (prestress forces, internal pressure at the design level and temperature loads) and the rest of the increments are carefully chosen as a fraction of the design pressure. This decision is taken so as not to cause any excessive non-linearity within the load increments. Analyses are performed at the following pressures (N/mm^2):

2.66, 3.75, 3.99, 4.665, 4.825, 5.32, 5.985, 6.65,

7.98, 8.645, 9.975, 11.305

The constant stiffness method (initial stress method) is used for all cases analysed in this section. An average of 10 iterations per increment were required for the convergence of the solution. Iterations within each load increment are terminated when a norm of residuals has reached a specified tolerance of 3×10^{-2}. Figure 5 shows the collapse mode given a load factor of 4.25.

The analyses also take into account the changing material properties with time and have been performed for 10 years, 20 years and 30 years in terms of prestress losses and material properties.

The obtained results of these analyses are obtained but not reported in the forms of pressure-deflection curves stud loads, bifurcation and liner rupture under the crack patterns of the vessels. Using the crack widths obtained previously for the liner yielding and rupturing, the analytical results show that due to the influence of the liner the load carrying capacity is increased by about 15/%.

4. SUMMARY AND CONCLUSIONS

A three-dimensional finite element analysis and solution procedures have been developed for the non-linear and rupturing conditions of a concrete vessel using Endochronic Theory. The analysis is first applied to the Oldbury Vessel with an anchored liner. The analytical results compared well with those obtained from the site monitoring under operational conditions. The safety margin obtained is closed with 15% to the model test carried out on this vessel by Hayetal (1968).

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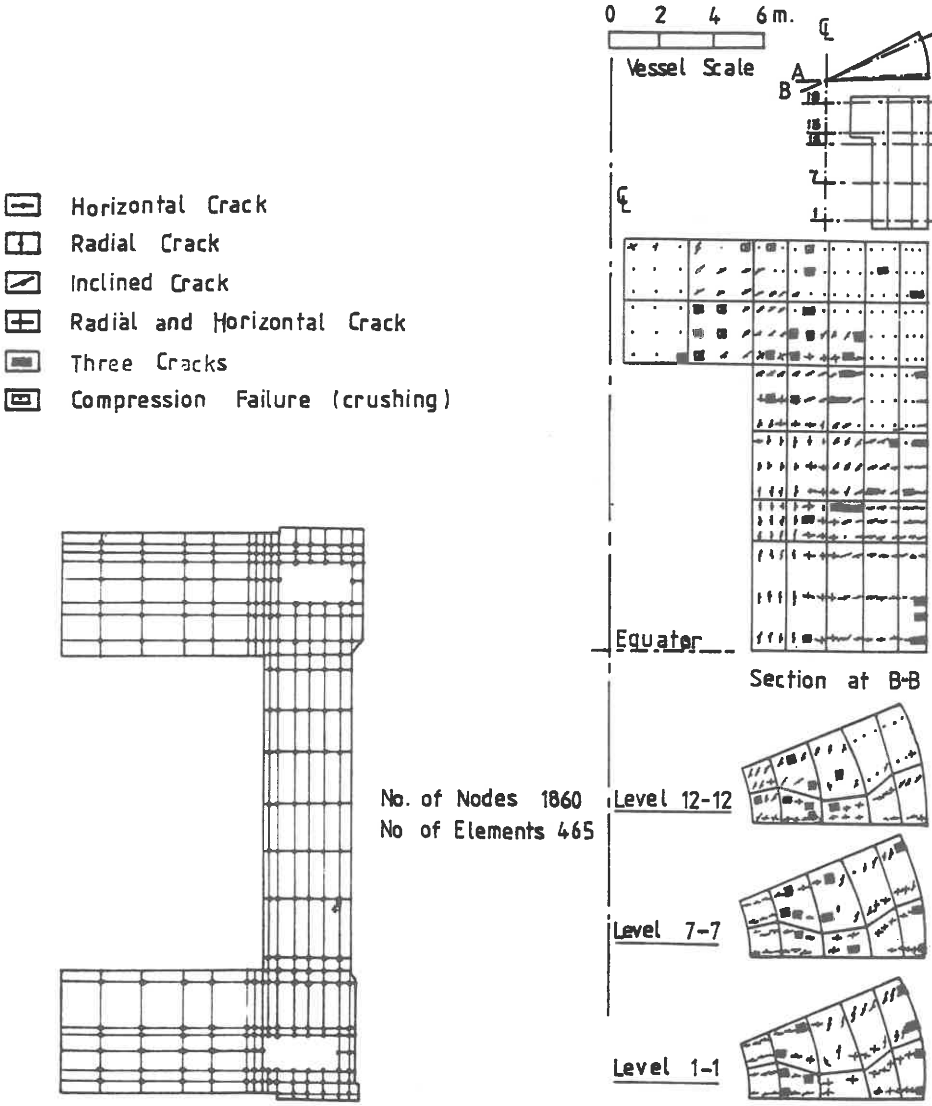

Figure 1 Crack Pattern of the Vessel

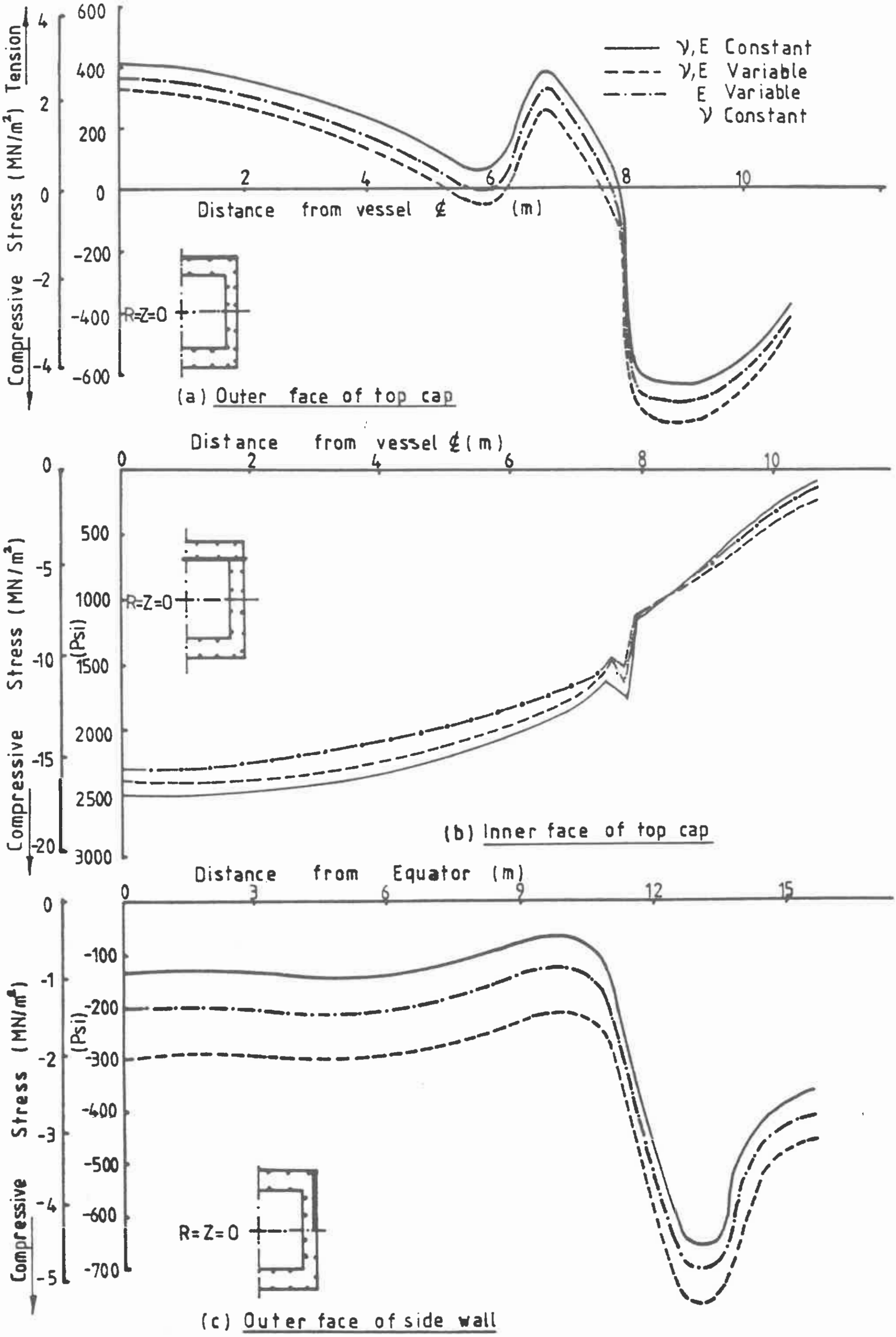

FIG 2 Circumferential stresses - operating condition only

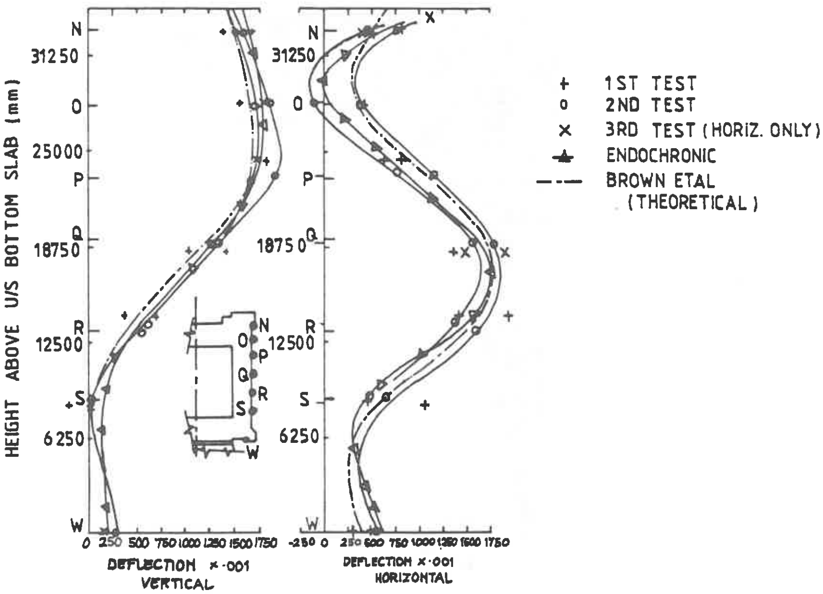

Figure 3 Wall horizontal and vertical deflections

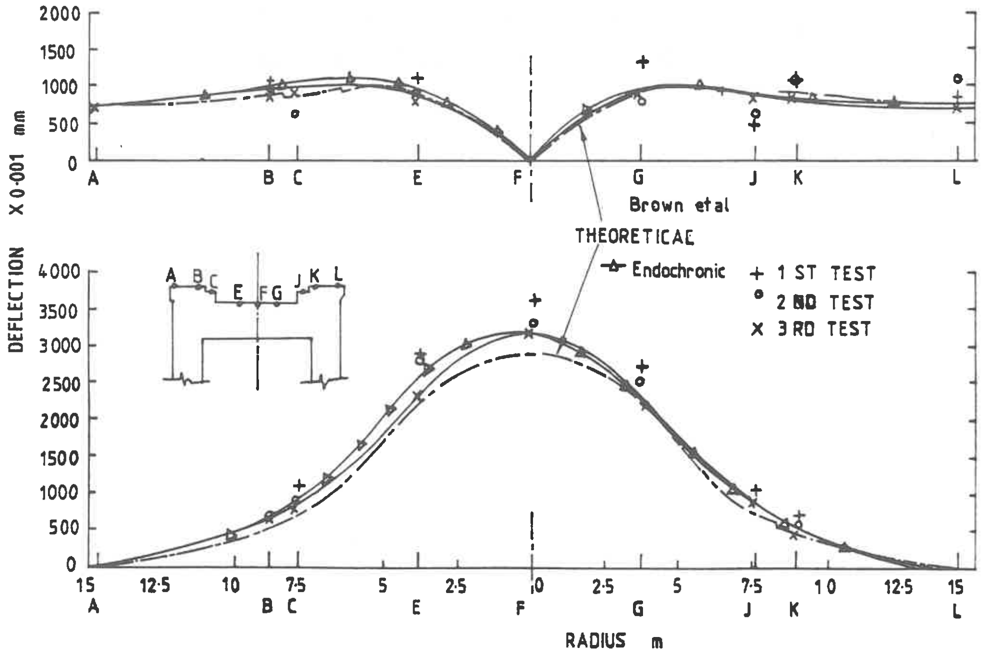

Figure 4 Top slab horizontal and vertical deflections

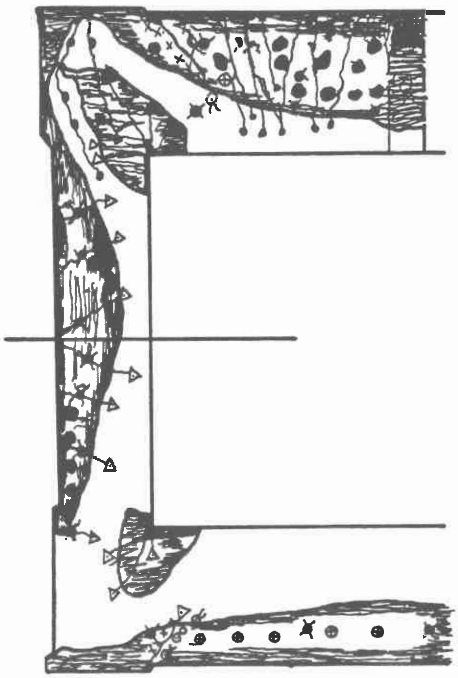

Fig. 5 OLDBURY PRESTRESSED CONCRETE REACTOR PRESSURE VESSEL

(P_G = 11 305 MN/ m^2)