The limit state analysis of prestressed concrete nuclear pressure vessels

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

1 INTRODUCTION

Prestressed concrete pressure vessels have been analysed, designed and constructed. Various numerical tools exist for the analysis of these structures (1-11). The experimental tests on scaled models have predicted various modes of failure and safety margins. From the vast amount of information now available, this paper attempts to present a limit state approach. Equations have been developed to predict flexural and shear failure in the wall of the vessel. When the resistance of the compressive area in the top or bottom closures or slabs is reduced, the outside perimeter of the stand pipes develops, as predicted by experiments , circumferential plane of weakness. Under gas increasing pressure from within the main cavity, a complete punched-out failure of the central core of the slab can occur apart from general flexural cracks. The analysis presented considers the following effects:-

1. Minimum rupturing strength of the tendons
2. Concrete strength under complex loads
3. Limiting crack sizes affecting the integrity of the vessel
4. Rupturing strength of the liner crossing crack

Any one of the above cases defines the failure mode.

2 VESSEL WALLS UNDER FLEXURE AND SHEAR

The barrel wall is first assumed under flexure. With assumed crack positions the safety margin is computed. The computer program VESSEL shifts automatically the crack positions longitudinally and radially and with a new deflected shape, the safety margin is evaluated. Similarly all possible crack positions are investigated. Based on the entire crack position history, the mode of failure corresponding to the minimum safety margin is established. Using Fig. 1 it is simple to establish the following expression for flexural collapse:

Equilibrium of forces acting on AB zone

(1) $$C_c + T'_\phi - T_F = C'_c + T_\phi - T'_F$$

Since $x_1 = n_1 d$ and $x_2 = n_2 d$ and if δ'_z is the deflection of the wall at the crack zone, then the values of R', n_1 and n_2 are expressed as

(2) $$n_1 + n_2 = 1 - \left[\frac{\delta'_z}{2d} + \frac{2R^2_E \beta}{d\,\delta'_z} \left(\varepsilon_T + \frac{\delta_o}{2R_E} \right) \right]$$

(3) $$R' = [2R_E (\beta + \varepsilon_T (1 - 2\beta)) + \delta_o] \sec \alpha_c$$

where α_c = the wall rotation at the level of crack formation.

From expression (2) the values of n_1 and n_2 can be derived as

(4) $$n_1 = \frac{1}{4d} \left[2d - \delta'_z - \frac{(\varepsilon_T + \delta_o/2H_I).4H^2_I.\beta}{\delta'_z} - \frac{T'_F - T_F - T_\phi + T'_\varphi}{0.225\,\sigma_{cu}} \right]$$

(5) $$n_2 = \frac{1}{4d} \left[2d - \delta'_z - \frac{(\varepsilon_T + \delta_o/2H_I).4H^2_I\beta}{\delta'_z} + \frac{T'_F - T_F - T_\delta + T'_\phi}{0.225\,\sigma_{cu}} \right]$$

The resistence moment offered by the vessel at ultimate

(6) $$M_u = C_c(d_1 - \bar{x}) + T'_\phi(d'_1 - d') - \left[\frac{K_2}{K_1} P_G + \frac{K_3}{K_1} \right] (d_e - e)$$

$$= [F_v + T_F - T'_\phi] (d_1 - \bar{x}) + T'_\phi(d'_1 - d') - \left[\frac{K_2}{K_1} P_G + \frac{K_3}{K_1} \right] (d_e - e)$$

Where K_1, K_2, K_3 are constants depending on the vessel geometry, prestressing layout and strains in materials. The value of $\bar{x}$ is a value of x_1 or x_2 and $(d_e - e)$ is a specific value of R'.

The gas internal pressure P_G is related to the external loads F'_V as

(7) $$\left(F'_V - \frac{K_3}{K_1}\right)\frac{K_1}{K_2} = P_G$$

Both F'_V and P_G are given incremental values.

Apart from bending the shear forces at each incremental position are evaluated by resolving inward forces due to prestressing, steel liner and bonded reinforcement and outward forces due to gas pressure.

3 VESSEL CAPS UNDER FLEXURE AND SHEAR

Top and bottom enclosures or caps are analysed by matching the cap rotation with the barrel wall rotation. The cap is subjected to disturbing forces and moments due to gas pressures. The restoring forces and moments by vertical compression of longitudinally radial compression of circumferential prestressing. Equilibrium equations have been developed in which a provision is made for gas increasing pressure, loads from tendons, bonded reinforcement, crack sizes and plug failure (flexural-cum-nominal shear, principal tensile failure, principal compressive failure, shear-compressive failure). The final equation for flexure is written in compact form as

(8) $$\phi P_G R_I^2 \left(R_E - \bar{a} - 2_3 R_I \frac{\sin\phi}{\phi}\right)$$

$$= D_W R_E^3 \sin\phi \left(1 - \bar{a} = \frac{\sin\phi}{\phi}\right) + \left(\frac{K_2}{K_1} P_G + \frac{K_3}{K_1}\right)(\bar{a})$$

$$+ T_F (d_I - \bar{x}) + T'_\phi (\bar{x} + d')$$

Where D_W is the self weight and ϕ is angle of vessel sector under consideration.

Where plug failure due to shear is investigated, Campbell-Allen (1969) suggested expressions based on parabolic shear distribution is adopted. A direct relationship of the gas increasing pressure and the shear plug failure has been derived for the vessel by Bangash (1982).

(9) $$P_G = \frac{2}{(x_2 - d \cot\gamma)^2}$$

$$\int_{x^2 - H\cot\gamma}^{x_2} [B'(\sigma_o + \sigma_1)^{k'} \tan\gamma - \sigma_o] R_x dR_x$$

$$= \frac{1}{(x_2 - d \cot \gamma)^2}$$

$$x[B'(\sigma_o + \sigma_1)^{k'} \tan \gamma - \sigma_o(2x_2 d\cot\gamma - d^2\cot^2\gamma)$$

4. APPLICATION TO VESSELS

The Limit State Analysis is applied to Oldbury and Dungeness B vessels. Figures 2 and 3 show the relationship between the gas increasing pressure, deflections, cracks, strains and levels of safety margins. The results of this analysis are compared with the finite element analysis by Bangash (1982) using Program ISOPAR. Both sets of results are in close agreement.

5. SUMMARY AND CONCLUSIONS

A limit state analysis is presented for concrete nuclear vessels in which flexural and shear modes are included. The results obtained are checked against those obtained from the finite element analysis. This analysis can be used for all concrete circular structures subjected to internal and external incremental loads.

REFERENCES

Bangash, Y. et al (1980). The influence of thermal creep on the operational behaviour of complex structures. Int.Conf. Fundamental Creep and Shrinkage, Laussane, Switzerland.

Bangash, Y. 1978. Movements in prestressed concrete reactor vessels. Nucl. Eng. & Design, vol. 50, pp 463-473.

Bangash, Y. 1981. The automated three-dimensional cracking analysis of prestressed concrete vessels. 6th SMIRT Conf. Paris, paper H3/2.

Bangash, Y. 1982. Reactor pressure vessel design and practice. Prog. Nucl. Energy, vol. 9, No. 1 pp 1-56.

Rashid, Y.R. 1968. Ultimate strength analysis of prestressed concrete pressure vessels. Nuclear Eng. Design 7, 334-344.

Bangash, Y. 1983. Containment vessel design and practice. Progress in Nuclear Energy, vol. 11, No. 2, pp 107-181.

Brown, V. Bland, A. 1975. The operators view of the first seven years service of the concrete pressure vessels at Oldbury-on-Severn power station. Conf. Pressure and Containment Vessels, York, England.

Langan, D. and J.R. Smith 1968. 10th Scale model of Marlepool Pressure Vessel - Introduction Statement. Structural Research Laboratory, Taylor Woodrow Construction Ltd.

Takeda, T. et al 1974. Pressure Tests on PCRV 7th FIP Conf. New York

Brading, K.F. et al 1969. Elastic and ultimate pressure tests on the tenth scale model of the Dungeness B Concrete Pressure Vessel. Model techniques for prestressed concrete pressure vessels. Proc. Conf. BNES, London.

Anderson, S.I. et al 1973. The Scandinavian PCRV Model Project: Stress calculation and experimental verification. 2nd SMIRT Conf. Berlin paper H5/3.

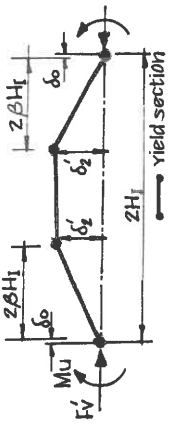
Campbell A.D. et al (1969) The use of simplified models for the design of end slabs. Conf. Model Technique. BNES.

l_c = length of crack = $\sqrt{(d-\bar{x})^2 + (2\beta H_I - H_I)^2}$

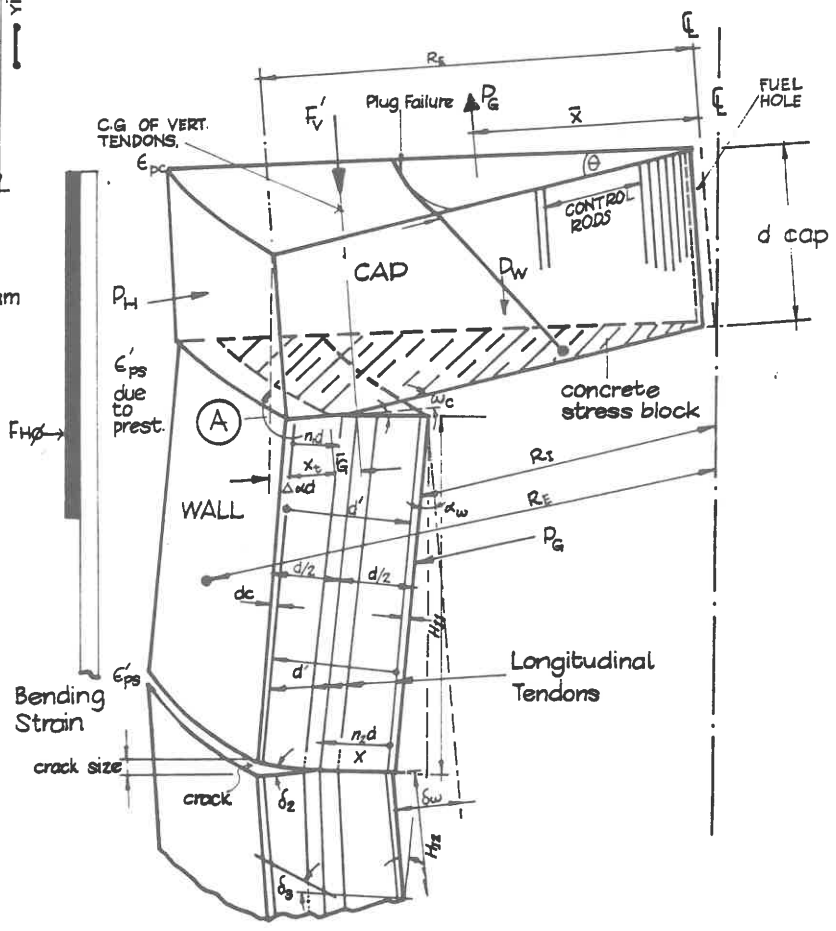
ω_c = crack size at (A)

$= \xi\{(\epsilon^*_{pb} - \epsilon'_{ps})\cdot\bar{J} + (\epsilon_{pc} - \epsilon'_{ps})\} * x\left[(d-\hat{x})^2 + (2\beta H_I - H_I)^2\right]^{1/2}$

ω_{Lo} = Longitudinal crack = $2R_E \cdot \sin\theta\,(\epsilon^*_{pb} - \epsilon'_{ps})$



Key Diagram



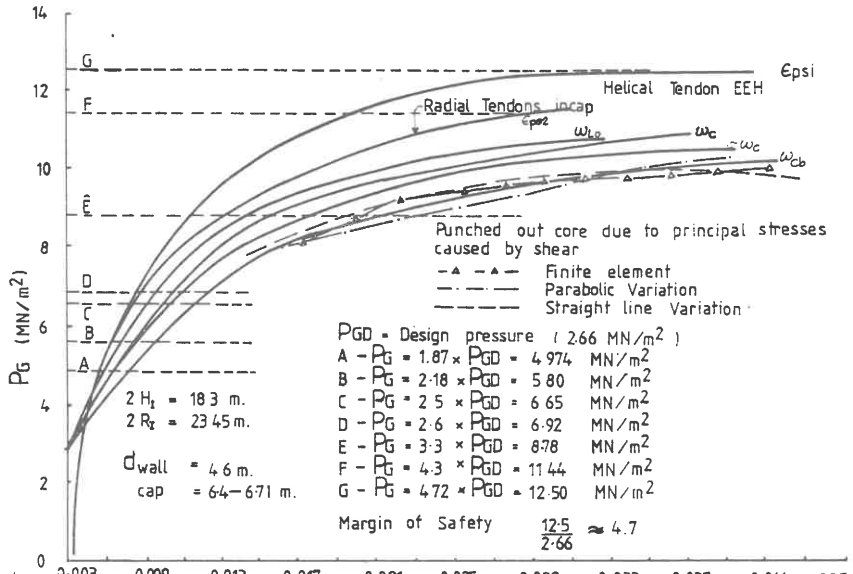
δ_2 = horiz. crack

$= \bar{J}(H_I + d)(\epsilon^*_{pb} - \epsilon'_{ps})$,

where $\bar{J} = R_E / \xi 2\beta\theta$

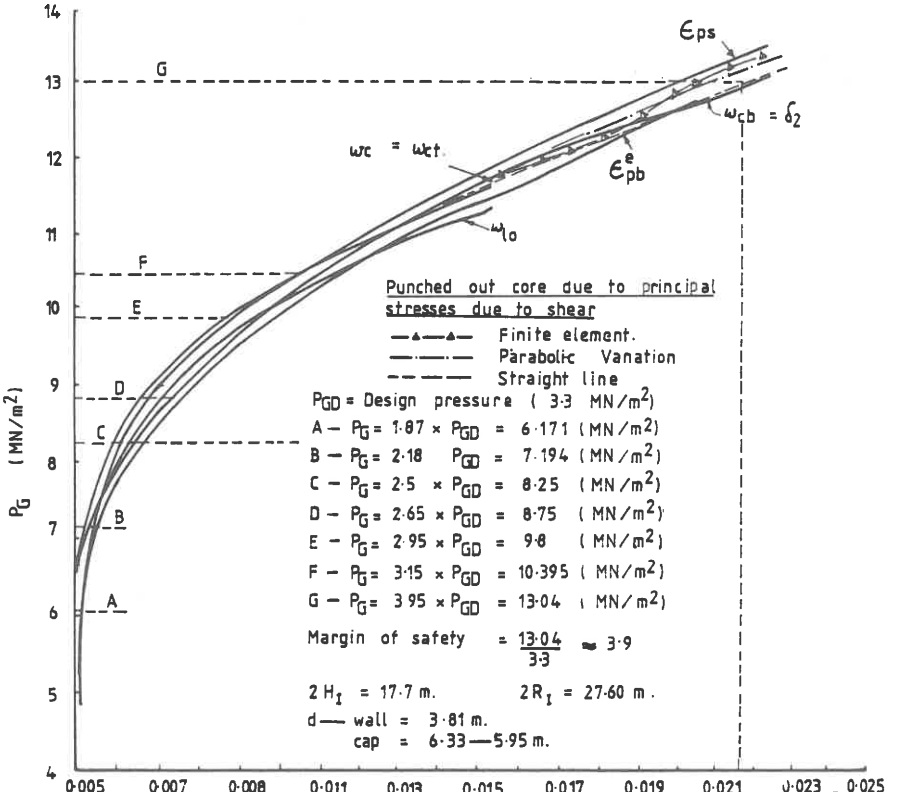
where $\xi = R_E / H_I(1-2\beta) + d$; $\bar{J} = H_I(1-2\beta) + d \,/\, 2\beta I$

Figure 1 Collapse Mechanism.



Crack width top cap & wall (mm.)		30		60		90	120	150		180
Crack width bottom cap (mm.)			40			70		100		150
Top cap central deflection (mm.)		40		60		80		100		120
Bottom cap central deflection (mm.)		9	18	27		35	43	51		59
Wall horizontal defl (mm)		7·5	12·5	17·5	22·5	27·5	32·5	37·5	42·5	47·5	52·5
$\hat{x}$ (m)	0·4				0·30				0·10 constant	

Figure 2 : Oldbury Reactor Vessel – Pressure versus cracks & deflections



Crack width top cap & wall (mm.)	5	15	25	35	45	55	65	75	85	95	100
Crack width bottom cap (mm.)	8	16	24	32	40	48	56	64	70	78	
Top cap central deflection (mm.)	9	12	15	18	21	24	27	30	32	38	
Bottom cap central defl. (mm.)	7	10	12·5	15	17·5	20	22·5	25·0	27·5	30	
Wall horiz. defl (mm.)	10	15·0	20	25	30					40	
x (m)	0·4				0·2				0·1	Constant →	

Figure 3 : Dungeness B Reactor vessel — pressure versus cracks & deflections.