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The ultimate strength analysis of prestressed containment vessel

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ABSTRACT

The ultimate strength analysis of presented contaminated vessels is proposed in this paper. Equations have been developed to predict the flexural and shear failure in the wall of this type of vessel. The analysis is applied to Oldburg and Dungeness B vessels. The results are compared with three-dimensional finite element analysis by using the computer program OBAID. Both sets of results are in close agreement.

INTRODUCTION

Prestressed concrete containment vessels for pressurized water reactors (PWR) and boiling water reactors (BWR) have been fully reviewed by various authors (Al-Obaid 1984, 1986, 1989, 1992, 1993; Brading & Hills 1969; Stevenson 1980a). Several methods of analysis and design are discussed by Al-Obaid (1984, 1989, 1992), Brading & Hills (1969) and Stevenson (1980a, 1980b).

In this paper, prestressed concrete pressure vessels have been analyzed, designed and modeled. Various numerical tools exist for the analysis of these structures. 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 an ultimate strength approach. Equations have been developed to predict flexural and shear failure in the wall of a 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, a circumferential plane of weakness as predicted by experiments. Under increasing gas 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 a crack

Any one of the above cases defines the failure mode.

VESSEL WALLS UNDER FLEXURE AND SHEAR

The barrel wall is first assumed to be under flexure. With assumed crack positions, the safety margin is computed. The computer program OBAID automatically shifts the crack positions longitudinally and radially and with a new deflected shape. The safety margin is then evaluated. Similarly, all possible crack positions are investigated based on the entire crack position history. Then the mode of failure corresponding to the minimum safety margin is established. The aim is to investigate the crack positions of the barrel wall under flexure. Using Fig. 1 it is simple to establish the equilibrium equations for flexural collapse.

Equilibrium of forces acting on the AB zone are

$$C_c + T_Q' - T_F = C_c' + T_Q - T_F'. \tag{1}$$

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,

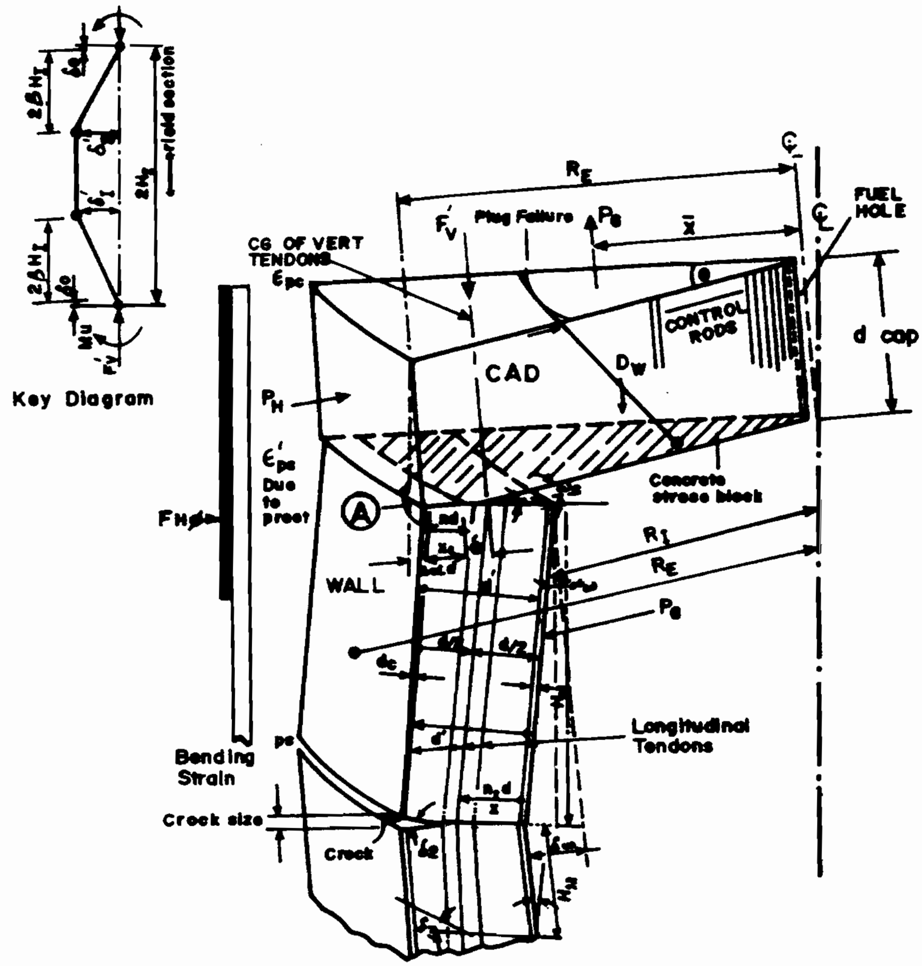


Fig. 1. Collapse mechanism.

then the values of R', n_1 and n_2 are expressed as

$$n_1 + n_2 = 1 - \left[\frac{\delta_z'}{2d} + \frac{2R_E^2\beta}{d\delta_z'}\left(\epsilon_T + \frac{\delta_0}{2R_E}\right)\right] \tag{2}$$

$$R' = [2R_E(\beta + \epsilon_T(1 - 2\beta)) + \delta_0] \sec \alpha_c \tag{3}$$

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

$$n_1 = \frac{1}{4d}\left[2d - \delta_z' - \frac{(\epsilon_T + \delta_0/2H_I)\cdot 4H_I^2\cdot\beta}{\delta_z'} - \frac{T_F' - T_F - T_o + T_o'}{0.225\sigma_{cu}}\right] \tag{4}$$

$$n_2 = \frac{1}{4d}\left[2d - \delta_z' - \frac{(\epsilon_T + \delta_0/2H_I)\cdot 4H_I^2\cdot\beta}{\delta_z'} + \frac{T_F' - T_F - T_\delta + T_o'}{0.225\sigma_{cu}}\right] \tag{5}$$

The resistance moment offered by the vessel at ultimate load is

$$\begin{aligned} M_u &= C_c(d_1 - \bar{x}) + T_o'(d_1' - d') - \left[\frac{K_2}{K_1}P_G + \frac{K_3}{K_1}\right](d_e - e) \\ &= [F_v + T_F - T_o'](d_1 - \bar{x}) + T_o'(d_1' - d') \\ &\quad - \left[\frac{K_2}{K_1}P_G + \frac{K_3}{K_1}\right](d_e - e). \end{aligned} \tag{6}$$

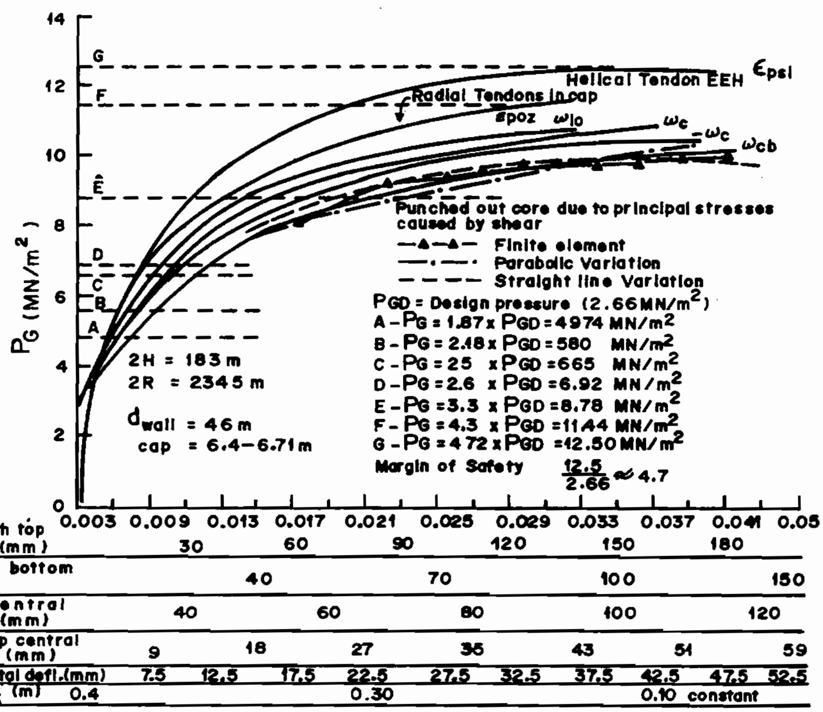
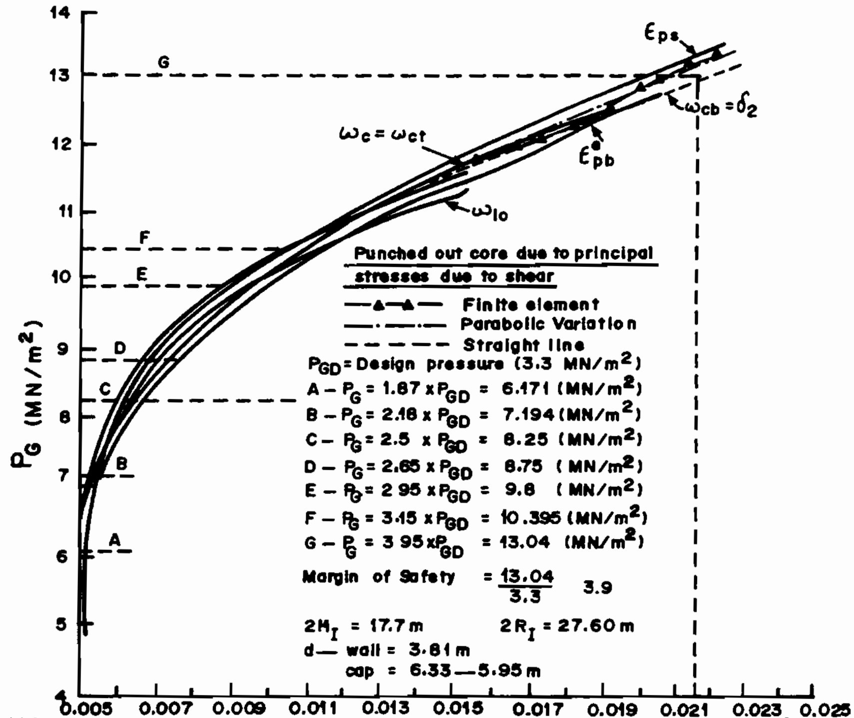


Fig. 2. Dungeness B reactor vessel—pressure versus crack and deflections.



Crack width top cap & wall (mm)	5	15	25	35	45	55	65	75	85	95	100
Crack with 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	15.0	17.5	20.0	22.5	25.0	27.5	30.0
Wall horiz. defl. (mm)		10	15	20	25	30					40
$\bar{x}$ (m)	0.4				0.2				0.1	Constant	

Fig. 3. Oldburgy reactor vessel—pressure versus crack and deflections.

Where K_1, K_2 and 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 internal gas pressure P_G is related to the external loads F'_v as

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

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.

VESSEL CAPS UNDER FLEXURE AND SHEAR

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

$$\phi P_G R_I^2\left(R_E - \bar{a} - 2_3 R_I \frac{\sin\phi}{\phi}\right) = D_W R_E^2 \sin\phi\left(1 - \bar{a} - \frac{\sin\phi}{\phi}\right) + \left(\frac{K_2}{K_1} P_G + \frac{K_3}{K_1}\right)(\bar{a}) + T_F(d_I - \bar{x}) + T'_\phi(\bar{x} + d') \quad (8)$$

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

Where plug failure due to shear is investigated, expression suggested by Campbell-Allen & Low (1968), based on parabolic shear distribution are adopted (Al-Obaid 1993). A direct relationship of the increasing gas pressure and the shear plug failure has been derived for this type of vessel by Brown & Bland (1975) in which

$$P_G = \frac{2}{(x_2 - d\cot\Upsilon)^2}\int_{x^2 - H\cot\Upsilon}^{x_2} [B'(\sigma_0 + \sigma_1)^{k'} \tan\Upsilon - \sigma_0] R_x \, dR_x$$

$$= \frac{1}{(x_2 - d\cot\Upsilon)^2} x[B'(\sigma_0 + \sigma_1)^{k'} \tan\Upsilon - \sigma_0(2x_2 d\cot_\Upsilon - d^2 \cot_\Upsilon^2)$$

APPLICATION TO VESSELS

Ultimate strength analysis is applied to Oldbury and Dungeness B vessels. Figures 2 & 3 show the relationship between the increasing gas pressure, deflections, cracks, strains and levels of safety margins. The results of this analysis are compared with the finite element analysis by Al-Obaid (1992, 1993) using the computer program OBAID. Both sets of results are in close agreement.

NOTATION

C_c, T'_ϕ, T_F C'_c, T_ϕ, T'_F	Forces acting on AB Zone
δ'_z	deflection of the wall
α_c	the wall rotation at the level of crack formation
K_1, K_2, K_3	constant parameters
M_u	resistance moment
P_G	the internal gas pressure
F'_v	the external loads
σ_{cu}	ultimate or critical stress normal to the closed crack
d	wall thickness (m)
R_1, R_E	effective internal and external radii respectively
$\bar{a}$	radius curvature of meridian
ϕ	angle of vessel
Δ_w	self weight
Υ	shear strain
H	internal height

B'	band width or hoop tendons spacing
β	coefficient for aggregates
E^{β}	elastic modulus at β
ϵ_T	tensile strain

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تحليل القدرة القصوى
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خلاصة

يتناول هذا البحث بالتحليل مدى قدرة تحمل الاوعية الاحتوائية الخرسانية سابقة الاجهاد.

ويتطرق البحث إلى الدراسة المستمرة لتطوير معادلات لحساب الانهيارات القاصة والمتعرجة في حوائط الاوعية الخرسانية وقد تم تطبيق هذا التحليل على كل من وعائي اولدبرج Oldburg ودنجنس Dungeness باستخدام برنامج الحاسب الآلي OBAID ويقدم البحث تقريرا عن نتائج الوعائين.