SHEAR STRENGTH OF END SLABS OF PRESTRESSED CONCRETE REACTOR VESSELS

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SUMMARY

Prestressed concrete reactor vessels (PCRV's) have been adopted for primary containments in most large high-temperature gas-cooled reactor installations. The most common configuration for PCRVs is a right-vertical cylinder with thick end slabs.

In order to assess the integrity of a PCRV it is necessary to predict the ultimate strength of the end slabs. The complexity of the basic mechanism of shear failure in the PCRV end slabs has thus far prohibited the development of a completely analytical solution. However, many experimental investigations on PCRV end slabs have been conducted over the past decade. This information makes it possible to establish empirical formulae for the ultimate strength of PCRV end slabs. The basis and development of an empirical shear-flexure interaction expression is presented in this paper.

A review of test data reported in the literature has shown that parametric studies conducted by the University of Illinois, Taylor Woodrow Construction, and the University of Sidney encompass the full range of credible design conditions for PCRV end slabs. The results of these tests were evaluated and an interaction equation of the following form was derived:

$$\sigma_g = \frac{K_1 D \sqrt{f_c'}}{R + \dfrac{K_2 D \sqrt{f_c'}}{\sigma_f}}$$

Where K_1, K_2 = constants
f_c' = compressive strength of concrete
D = depth of end slab
R = radius to reference surface through the end slab
σ_g = failure pressure
σ_f = pressure calculated from a flexural analysis

The precedent for this approach has been established by numerous investigators of the punching shear strength of slabs. It was found that this approach offers a convenient and rational method of accounting for end slab geometry; material properties, the presence of bonded reinforcing steel; and the location, size, and level of stress of circumferential and longitudinal prestressing elements. Constants in the expression were determined statistically from the results of about seventy end slab tests.

The application of the shear-flexure equation requires the determination of the flexural strength of the end slab as the first step in the interaction procedure. The development of the flexural analysis follows the classical yield-line theory. The mechanism of a flexural failure is formed by a series of wedge-shaped sections, each bounded by radial cracks. The relationship between the internal pressure and the resistance provided by the prestressing and reinforcing elements in the end slab is established by equilibrium consideration.

The validity of the derived equation was verified by comparison with the results of PCRV scale model tests. Excellent correlation between predicted and observed strengths was obtained.

1. INTRODUCTION

Prestressed concrete reactor vessels (PCRVs) have been selected for use as primary containment for high-temperature gas-cooled reactors. PCRVs offer the advantages of on-site fabrication and an inherent high degree of safety due to the highly redundant nature of the prestressing systems. The configuration used in current designs is in the form of a cylindrical barrel capped with flat end slabs. A multicavity PCRV in which steam generators are located within cavities in the barrel wall is shown in Figure 1.

The barrel strength is well defined because it is governed by the properties of prestressing steel and bonded reinforcement. The complexity of the basic mechanisms of failure in the PCRV end slabs has prohibited the development of a completely analytical solution at the present state of knowledge. However, in the past decade, many experimental investigations on the PCRV end slabs were conducted in the United States and abroad. The available test information makes it possible to establish empirical formulas for the determination of ultimate strength of PCRV end slabs. The basis and development of an empirical shear-flexure interaction expression for the prediction of the ultimate strength of PCRV end slabs are presented in this paper.

While numerous tests have been conducted for verification of prototype designs, it was decided to restrict the current phase of investigation to those studies which encompassed a wide spectrum of important parameters affecting the ultimate strength of PCRV end slabs. Test series conducted at the University of Illinois (Ref. 1, 2), Taylor Woodrow Construction (Ref. 3), and the University of Sidney (Ref. 4) were studied. The effects of penetrations and liners within the range normally encountered in practice were shown to have insignificant effect on head strengths in these and other investigations. Consequently, it was not considered necessary to modify the procedure to account for the presence of penetrations in PCRV end slabs in the present study.

2. DEVELOPMENT OF SHEAR-FLEXURE INTERACTION EXPRESSION

2.1 Shear-Flexure Interaction

The mechanism of shear failure observed in PCRV and slabs bears a great deal of similarity to the problem of shear failure of slab and column intersections. Moe (Ref. 5) gives an excellent analysis of the influence of the triaxial stress condition on the onset of cracking and on the ultimate strength. The relationship between flexural strength and shear strength has been observed by numerous investigators and is well documented in the literature (Ref. 5, 6).

Three principal variables affect shear strength of concrete slabs, namely, (1) concrete strength, (2) the relationship between loaded area and slab thickness, and (3) the relationship between shear and moment in the vicinity of the loaded area. Pursuing the approach of Elstner and Hognestad (Ref. 6), Moe was able to obtain excellent correlation with experimental results with a shear-flexure interaction expression (Ref. 5).

Similar to Moe's development, an expression of shear-flexure interaction may take the following form:

$$\frac{P}{P_s} + C\,\frac{P}{P_F} = 1 \qquad (1)$$

where, P = Failure load = $\pi R^2 \sigma_g$

P_s = Ultimate shear load = $K\ 2\pi RD\sqrt{f'_c}$

P_F = Ultimate flexural load = $\pi R^2\ \sigma_F$

C = Constant

R = Radius of critical section

K = Constant

D = Head depth

σ_g = Failure pressure of the head

σ_F = Pressure corresponding to flexural failure of the head

f'_c = Compressive strength of concrete

Rewriting Eq. 1:

$$\frac{P}{P_s}\left[1 + C\frac{P_s}{P_F}\right] = 1 \tag{2}$$

$$\frac{P}{P_s} = \frac{1}{1 + C\dfrac{P_s}{P_F}} \tag{3}$$

By substituting the values for P, P_s, and P_F, Eq. 3 can be written as:

$$\frac{\pi R^2\ \sigma_g}{2K\pi RD\sqrt{f'_c}} = \frac{1}{1 + C\dfrac{2K\pi RD\sqrt{f'_c}}{\pi R^2\ \sigma_F}} \tag{4}$$

$$\sigma_g = \frac{2KD\sqrt{f'_c}}{R + \dfrac{2CKD\sqrt{f'_c}}{\sigma_F}} = \frac{K_1 D\sqrt{f'_c}}{R + \dfrac{K_2 D\sqrt{f'_c}}{\sigma_F}} \tag{5}$$

where, K_1 = 2K

K_2 = 2CK

The constants, K_1 and K_2, and the pressure corresponding to ultimate strength in flexure, σ_F, must be determined.

2.2 Flexural Strength of PCRV End Slabs

The mechanism of flexural failure of PCRV end slabs is formed by a series of sectors, each rotating about an axis near the outer surface of the vessel wall. Because the sectors remain virtually rigid, the yield line analysis (Ref. 7) would apply directly to the evaluation of the flexural strength of the slab.

Flexural failures in the PCRV end slabs were demonstrated in a series of models tested at the University of Illinois (Ref. 1). The development of the analysis for the flexural strength of the end slab is reported in Ref. 1 and will not be repeated herein.

2.3 Determination of Empirical Constants

As suggested by Wood (Ref. 8), a very powerful method of obtaining experimental relations is by plotting the most significant parameter in a nondimensional form. The information used to develop the shear-flexure interaction expression was extracted from Refs. 1, 2, 3 and 4. The data will not be repeated here in order to conserve space.

Upon inspection of the left side of Eq. 4, it is apparent that the expression

$$\frac{\pi R^2 \sigma_g}{2K\pi \; RD\sqrt{f'_c}}$$

is equivalent to the nominal shear at a radius R due to the failure pressure divided by a constant times the square root of the concrete compressive strength.

Likewise, the expression

$$\frac{2CK\pi \; RD\sqrt{f'_c}}{\pi R^2 \sigma_F}$$

is equivalent to a constant times the square root of the concrete compressive strength divided by the nominal shear at a radius R due to the pressure σ_F (pressure corresponding to flexural failure of the end slab).

letting

S_i = The shear index

$$= \frac{\pi R^2 \sigma_F}{2 \; \pi RD\sqrt{f'_c}} = \frac{R \sigma_F}{2D\sqrt{f'_c}} \qquad (6)$$

F_i = The failure index

$$= \frac{\pi R^2 \sigma_g}{2\pi \; RD\sqrt{f'_c}} = \frac{R \sigma_g}{2D\sqrt{f'_c}} \qquad (7)$$

It is apparent from Eq. 6 and Eq. 7 that choice of the radius of the critical section, R, is somewhat arbitrary. The best correlation of data was obtained for the section at $\frac{D}{2}$ form the wall. It is believed that this zone is less sensitive to the extreme confining stresses imposed by vertical and horizontal prestress.

Substituting Eq. 6 and Eq. 7 into Eq. 4 will yield

$$\frac{F_i}{K} = \frac{1}{1 + \frac{CK}{S_i}} \qquad (8)$$

which may also be written in the following form:

$$F_i = \frac{AS_i}{BS_i + 1} \qquad (9)$$

where

$$A = \frac{1}{C}$$

$$B = \frac{1}{CK}$$

The constants A and B were determined by minimizing the standard deviation of

$$\frac{F_{i\ (test)}}{F_{i\ (calc)}}$$

The values obtained are

$$A = 1.76,\ B = 0.059$$

The coefficients in Eq. 5 then become

$$K_1 = 2K = 60$$

$$K_2 = 2CK = 34$$

and the equation yields the following shear flexure interaction expression:

$$\sigma_g = \frac{60\ D\sqrt{f'_c}}{R + \frac{34D\sqrt{f'_c}}{\sigma_F}} \qquad (10)$$

Figure 2 shows the shear flexure interaction curve.

In order to accommodate the rather complex restraint conditions and geometry of some specimens, simplified assumptions were made to the method of flexural analysis presented in Ref. 1 to obtain the shear indices for the foregoing expression. These assumptions included neglecting bonded rebar, and the depth of concrete compression zones and defining the limiting edge rotation as the smaller of the yield rotation or 0.01 radian.

After examination of several prototype end slab designs, it was determined that the range of practical interest could be defined as $S_i < 30$. Having demonstrated the trend by the foregoing procedure, it was decided to eliminate end slabs of impractical proportions and refine the approach within this range. The shear indices were modified to include the contribution of bonded reinforcement, the effects of compression in the concrete, and based on the strain capacity of the prestressing elements. An improved correlation of the data in the range of $S_i < 30$ was obtained. The recommended equation for the prediction of ultimate strength based on a more detailed flexural analysis becomes

$$\sigma_g = \frac{70\ D\sqrt{f'_c}}{R + \frac{60\ D\sqrt{f'_c}}{\sigma_F}} \qquad (11)$$

The data used and the above expression are shown in Figure 3.

3. DISCUSSION

Data from 69 end slab tests covering a broad spectrum of edge constraint conditions were used to develop a shear-flexure interaction expression based on a simplified yield line flexural analysis. The approach was then refined within the range of practical interest, which is defined as $S_1 < 30$, by applying a more thorough flexural analysis. Inclusion of bonded rebar and the effects of concrete compression resulted in improved correlation of the data within this range.

The generality and applicability of the prediction equation should be considered with respect to the data used in its development. The test programs from which the data were extracted included studies of such parameters as (a) the presence of bonded reinforcement; (b) variation of the span-depth ratio; (c) variation of concrete strength; (d) the presence of penetrations; (e) the presence of barrel sections; and (f) variation of prestressing quantities, materials, and locations. With the exceptions of (d) and (e) above, these parameters are considered in the interaction expression. As stated previously, the presence of lined penetrations within the range normally encountered in practice has been shown to have small effect on head strength. The presence of barrel sections and interaction between the head and barrel have not been addressed in this paper.

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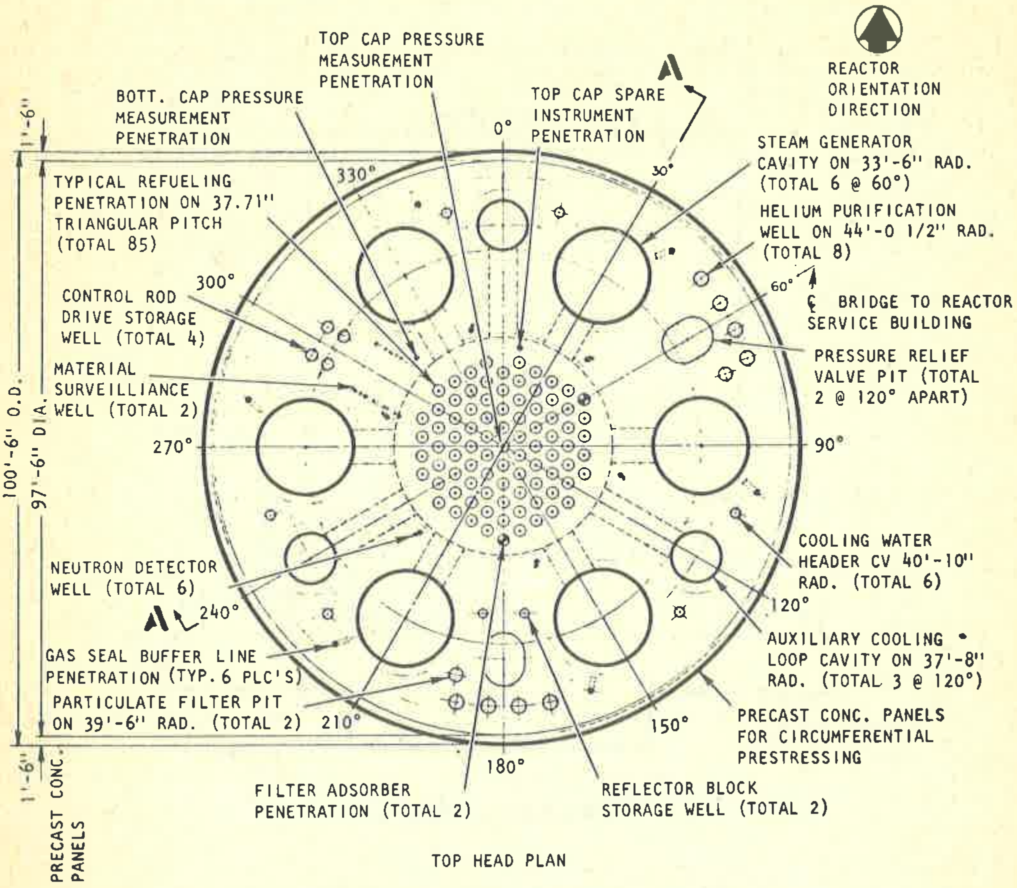

TOP HEAD PLAN

Fig 1(a) Multicavity PCRV for 1160 MW(e) HTGR

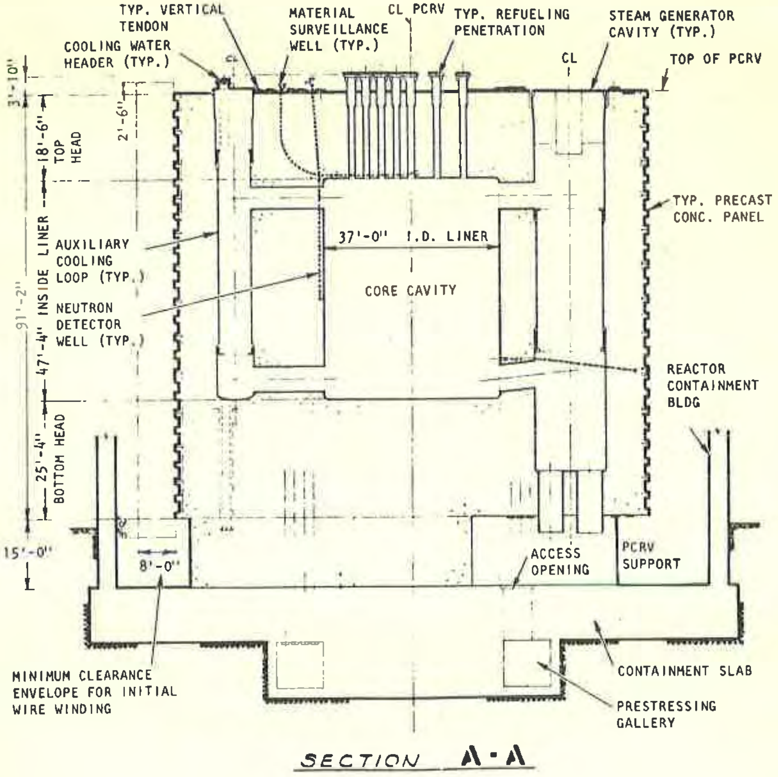

Fig 1(b) Multicavity PCRV for 1160 MW(e) HTGR

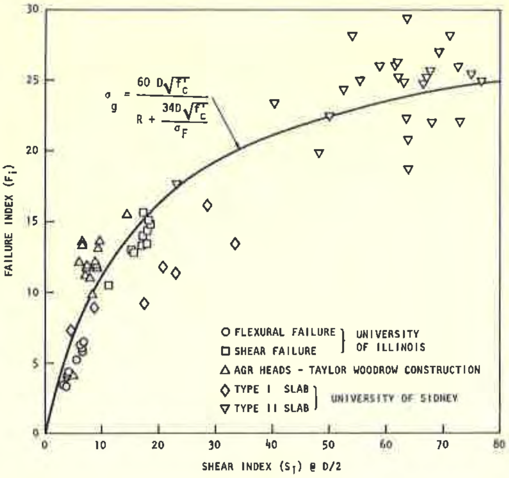

Fig 2 Shear-Flexure Interaction Curve for Sections at D/2 from Wall

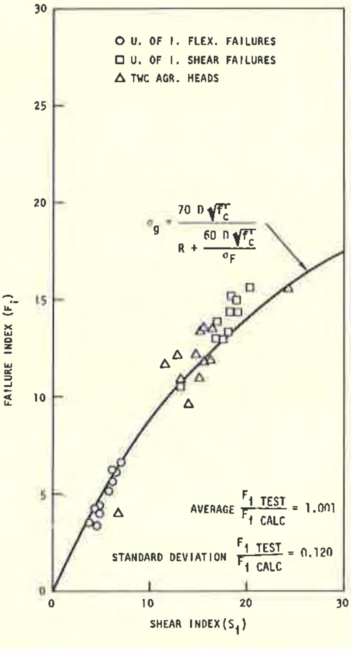

Fig 3 Shear-Flexure Interaction Curve Based on a Detailed Flexural Analysis