Bond Strength History in Prestressed Concrete Reactor Vessels

Y. Bangash
Middlesex Polytechnic, Faculty of Engineering and Applied Science, Queensway, Enfield, Middlesex EN3 4SF, U.K.
M. Ahmed
H.W. Structures Limited, Essex, U.K.

Abstract

An attempt has been made to study bond strength history in Prestressed Concrete Reactor Vessels (PCRV) which house the Advanced Gas-cooled Reactors. Three-dimensional non-linear analytical model has been developed in which the effect of bond is included. A finite element computer program is written in which solid, membrane, line and bond-linkage elements have been used to represent vessel concrete, steel liner, prestressing tendons and bond (between steel and concrete) respectively. Two experiments have been carried out in order to determine bond coefficients. A typical multi-cavity PCPV has been analysed for bond strength under gas increasing pressure at suitable intervals of its 30 years life

1. Introduction

Gas increasing pressure, load history and a cracking condition assume important roles in the vessel's short and long-term performance. Where the vessels have been bonded (grouted tendons), the ultimate load carrying capacity is influenced by the complex three-dimensional bond-slip phenomenon. This is the theme of the current research. In the tension zone within the vessel concrete, bond-slip takes place at the steel-concrete interface prior to cracking. It contributes to further cracking under loads and consequently affects the ultimate load capacity. Bond-slip behaviour is non-linear in nature and is influenced by many factors such as the strength of the concrete, roughness of the steel surface and diameter of the steel. As soon as bond breaks, the steel and concrete separates and wider cracks appear, producing greater slip. During and after the crack formation pre-stressing tendons carry most of the load and may deform plastically, thereby affecting the integrity of the vessel.

The bonded vessels under such conditions need to be investigated by sophisticated numerical techniques. In the present research, the finite element method is adopted in order to model the bond strength history of the vessels under increasing loads.

The scope of this paper is to analyse bonded and perfectly bonded prestressed concrete reactor vessels. For comparative study, an unbonded vessel is also analysed. The vessel chosen for the analyses is of multicavity type, in which boilers and circulators are housed within the vessel wall and cap thickness (1, 2). It is intended to house the High Temperature Gas-Cooled Reactor.

The main investigation is based on bond between the prestressing tendons and the vessel concrete. An attempt has been made to carry out analytical study on bonded vessels. In order to corroborate results, experimental tests have been performed on an octagonal prestressed concrete slab and pull-out specimens. Using parameters obtained from bond tests, the analyses have been carried out on the slab which represents the top cap of the concrete vessel for an advanced gas-cooled reactor (AGR). Realistic material models with regard to progressive cracking and compression of concrete, steel yielding and bond stress distribution have been developed for analysis, with and without the influence of temperature and creep effects.

2. Theoretical Model

A brief outline is given for the non-linear bond strength history of the vessel. The non-linearity considered are that of concrete, steel and bond-slip. Apply a load of $\Delta \underset{\sim}{P}_n$ where n is the load increment. Accumulate total load $\underset{\sim}{P}_n = \underset{\sim}{P}_{n-1} + \Delta \underset{\sim}{P}_n$ and $\underset{\sim}{R} = \Delta \underset{\sim}{P}_n$ where $\underset{\sim}{R}$ is the residual load vector. Solve $\Delta \underset{\sim}{U}_i = \underset{\sim}{K}^{-1} \underset{\sim}{R}$ where i is the interation number and $\underset{\sim}{K}$ is the stiffness matrix of the vessel. The Initial Stress Method is used as a non-linear solution technique. The incremental slip for the nodal displacements is given by

$$\Delta \underset{\sim}{S}_i = \underset{\sim}{T} \Delta \underset{\sim}{U}_i \qquad \text{eq. (1)}$$

where $\underset{\sim}{T}$ is the transformation matrix and $\Delta \underset{\sim}{U}_i$ are the element nodal displacements. The total slip at "i" iteration is given by

$$\underset{\sim}{S}_i = \underset{\sim}{S}_{i-1} + \Delta \underset{\sim}{S}_i \qquad \text{eq. (2)}$$

Total stress is computed as

$$\begin{aligned} \underset{\sim}{\sigma}_{bi} &= \underset{\sim}{\sigma}_{bi-1} + \Delta \underset{\sim}{\sigma}_{bi} \qquad \text{eq. (3)} \\ &= \underset{\sim}{\sigma}_{bi-1} + \underset{\sim}{E}_b (\underset{\sim}{\sigma}_{bi-1}) \Delta \underset{\sim}{\sigma}_i \end{aligned}$$

Here the state of the bond is checked, if the bond is broken, the stress is zero, i.e. $\underset{\sim}{\sigma}_{bi} = 0.0$ and S_{max} is obtained. If $|S_i| < S_{max}$ bond stress is computed. If $\underset{\sim}{\sigma}_b^T$ be the bond stress compatible with the slip S_i, the correct is computed as

$$\underset{\sim}{\sigma}_{bi} = \underset{\sim}{\sigma}_{bi} - \Delta \underset{\sim}{\sigma}_D \qquad \text{eq. (4)}$$

Total internal equivalent loads and residuals are calculated as

$$\begin{aligned} \underset{\sim}{P}_{int} &= \pi d L \underset{\sim}{T}^T \underset{\sim}{\sigma}_{bi} = \pi d L \underset{\sim}{T}^T E_b \underset{\sim}{T} \Delta \underset{\sim}{U}^e \\ &= K_b^e \Delta \underset{\sim}{U}^e \qquad \text{eq. (5)} \end{aligned}$$

$$\underset{\sim}{R} = \underset{\sim}{P}_n - \underset{\sim}{P}_{int}$$

where $\underset{6x6}{\underset{\sim}{K}_b}$ is the bond stiffness matrix given in Table 1.

The values of E are indicated in Fig.1.

3. Comparative Study of Results

Figure 2 shows the finite element mesh scheme for the multicavity vessel (2) treating The Vessel as perfectly bonded. Figure 3 shows finite element meshes at different levels. Using the above mentioned analysis, many plots for deformation at various ages have been obtained. Here only results for 10 and 30 years are shown in Figures 4 and 5. Similarly the same vessel has been analysed for unbonded condition. Coefficients for bond were obtained (1) using pullout-tests and from the slab test. At various stages the crack pattern was well disposed in case of a bonded vessel. In brief the ultimate load carrying capacity in case of a bonded tendon was enhanced by 18%.

4. Conclusion

Tests have been carried out for bonded and unbonded slabs. Results have been incorporated into bonded and unbonded vessels as parameters. Both types of vessels have been analysed for up to 30 years using Ahmlink and rigid bonded schemes. It has been found that where no cable defects exist, the bonded vessel can easily carry additional ultimate load of 18% of the design pressure.

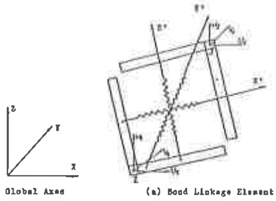
5. Acknowledgement

The authors are indebted to the Science Engineering Council for facilities extended in order to complete this research and to the Faculty of Engineering, Middlesex Polytechnic for typing the manuscript.

6. References

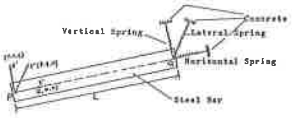
/1/ AHMED, M., "Bond Strength History in Prestressed Concrete Reactor Vessels", Ph.D. Thesis (CNAA) July 1983.

/2/ BANGASH, Y., "Reactor Pressure Vessel Design and Practice". Progress in Nucl. Energy, Vol.10, No.1, pp.69-124, 1982.

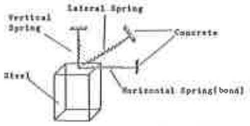


(a) Bond Linkage Element

X'Y'Z' - Local Axes



(b) Direction Cosines



(c) Bond Representation

Figure 1. Three Dimensional Bond Linkage Element

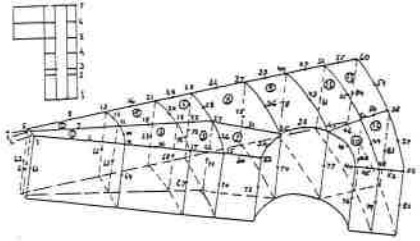
Table 1 - Stiffness Matrix and Load Vector for Bond-Linkage Element.

$$
[K_b]_{6\times6} = \pi dL
\left[\begin{array}{|c|c|c|c|c|c|}
\hline
\ell^2 E_h + p^2 E_v + \gamma^2 E_\ell & \ell_m E_h + pq\,E_v + \gamma s\,E_\ell & \ell_n E_h + \gamma t\,E_v & -\ell^2 E_h - p^2 E_v - \gamma^2 E_\ell & -\ell_m E_h - pq\,E_v - \gamma s\,E_\ell & -\ell_n E_h - \gamma t\,E_v \\
\hline
 & m^2 E_h + q^2 Ev + s^2 E_\ell & mn\,E_h + St\,E_\ell & -\ell m\,E_h - pq\,Ev - \gamma s\,E_\ell & -m^2 E_h - q^2 Ev - s^2 E_\ell & -mn\,E_h - st\,E_\ell \\
\hline
 & & h^2 E_h + t^2 Ev & -\ell n\,E_h - \gamma t\,E_v & -mn\,E_h - st\,E_\ell & -n^2 E_h - t^2 E_v \\
\hline
 & & & \ell^2 E_h + p^2 E_v + \gamma^2 E_\ell & \ell m\,E_h + pq\,E_v + \gamma s\,E_\ell & \ell n\,E_h + \gamma t\,E_v \\
\hline
 & \text{SYMMETRICAL} & & & m^2 E_h + q^2 E_v + s^2 E_\ell & mn\,E_h + st\,E_\ell \\
\hline
 & & & & & n^2 E_h + t^2 E_v \\
\hline
\end{array}\right]
$$

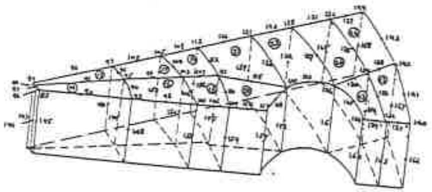
$$
\underset{\sim}{\Delta P}{}^{e}_{6\times1} = \pi dL
\left\{\begin{array}{l}
-\ell\,\Delta\sigma_h - p\,\Delta\sigma_v - \gamma\,\Delta\sigma_\ell \\
-m\,\Delta\sigma_h - q\,\Delta\sigma_v - s\,\Delta\sigma_\ell \\
-n\,\Delta\sigma_h - t\,\Delta\sigma_\ell \\
\ell\Delta\sigma_h + p\,\Delta\sigma_v + \gamma\Delta\sigma_\ell \\
m\Delta\sigma_h + q\,\Delta\sigma_v + s\,\Delta\sigma_\ell \\
n\Delta\sigma_h + t\,\Delta\sigma_\ell
\end{array}\right\}
$$

πdL - perimeter of the steel

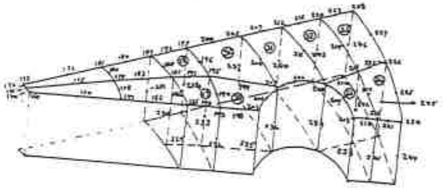
l,m,n, p,q,v, s,t. } - direction cosines.



Level 6-7



Level 5-6



Level 4-5

• – Node Number

O – Element Number

Figure 3 Dtailed Finite Element Mesh for Perfetly Bonded Reactor Vessel

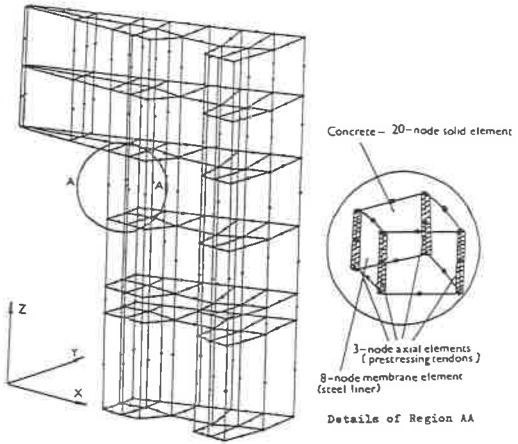


Figure 2 Finite Element of Perfectly Bonded Reactor Vessel

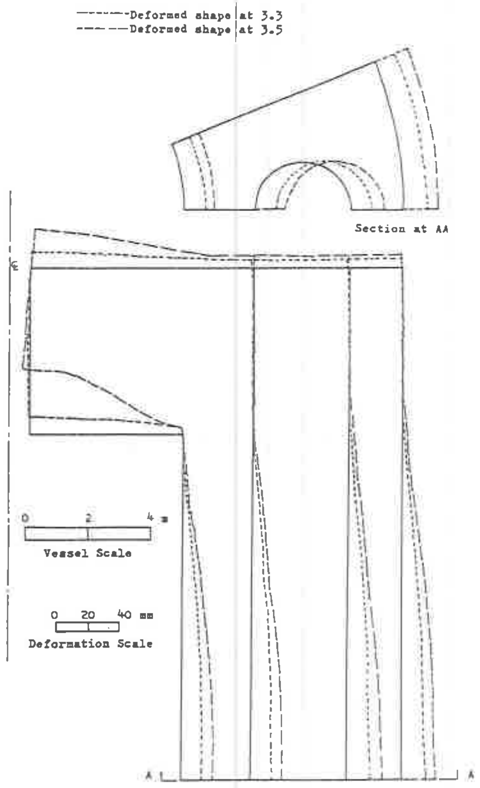


Figure 4 Deformed Shapes of Bonded Reactor Vessel
10 Years

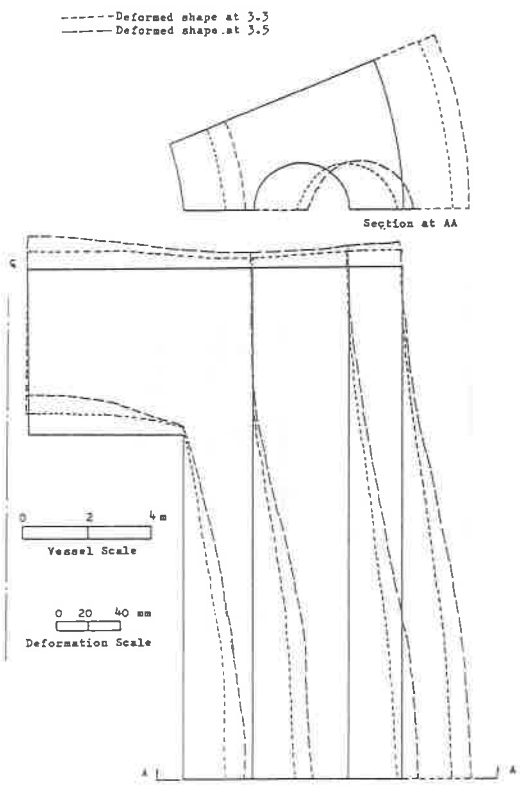


Figure 5. Deformed Shapes of Bonded Reactor Vessel
30 Years