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The pre-test analysis for overpressurization containment vessel using endochronic model

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ABSTRACT

This paper initially gives general steps of flow-cum-crack analysis using three-dimensional 32 nodded isoparametric elements together with line and bond-linkage elements. An endochronic model is used in which a provision is made for the increment of inelastic dialatancy variable, shear and bulk moduli. A set of material parameters obtained by fitting numerous test-data is used for the non-linear analysis of the Oldburg containment vessel. The endochronic model is then extended and is linked to a cracking analysis within the computer program **OBAID**. Certain analytical results such as displacements for low and high pressure-over pressurization are obtained. The results show agreement in certain areas with those obtained by other methods, and some disagreement at other areas of the solution domain.

NOTATION

σ_b	bond stress
$\Delta\epsilon_s$	change in steel strains over the bonded length
L_b	bond (embedded) length
d	diameter of steel
$\pi d L_b$	embedded surface area of steel
l, m, n, p, q, r, s, t	direction cosines of local axes with respect to global axes (ξ, η, ζ)
$\Delta S_h, \Delta S_v, \Delta S_t$	incremental slips in horizontal, vertical and lateral directions of steel bars
$\Delta\sigma_n, \Delta\sigma_v, \Delta\sigma_t$	incremental bond stresses in horizontal, vertical and lateral directions
δ, V, W	global displacements in X, Y, and Z directions
E_h, E_v, E_t	bond-slip moduli
T	transformation matrix
ΔP^e	incremental element load vector
$\Delta\sigma_b^e$	incremental element stress vector
$\Delta\delta^e$	incremental element displacement vector
E_b	bond-slip moduli matrix
K_b^e	bond-linkage stiffness matrix
ΔS	incremental element slip vector
δ	total global displacement vector

B	strain-displacement matrix
ϵ	strain vector
σ	stress vector
R	residual load vector
D_{12}, D_{13}	material matrix with cracks in directions of one and two, one and three
X, Y, Z	global system co-ordinate
ξ, η, ζ	local system co-ordinate
J	determinant of a Jacobean
δ_{ij}	Kronecker Delta ($\delta_{iJ=1}$ for $i = J$, otherwise zero)
σ_m	volumetric stress
K	bulk modulus
G	Shear modulus
$n_1, \beta_1, \beta_2, a_n$	coefficients
λ	inelastic dilatancy
D_T	material matrix
$\sigma_x, \sigma_y, \sigma_z$	stresses in x, y, z direction
$\tau_{xy}, \tau_{yz}, \tau_{xz}$	shear stresses in $x-y$, $y-z$, $z-x$ plane
$\Upsilon_{xy}, \Upsilon_{yz}, \Upsilon_{zx}$	shear stresses in $x-y$, $y-z$, $z-x$ plane
β	aggregate interlocking factor

INTRODUCTION

Several finite element studies have been carried out to analyze a 1:6 scale containment vessel model (Al-Obaid 1990). An attempt has been made in this paper to analyze the same containment vessel using Endochronic concrete failure theory. Another departure is to assume that concrete is represented by a sophisticated 3D-32 nodded isoparametric element in which the reinforcement is placed in the body of this element. The reinforcement is represented by 3D-4 nodded line element attached to a bond-linkage element (Al-Obaid 1984, 1986, 1992, 1993; Bazant & Bhat 1976; Bazant & Oh 1983) thus treating the reinforcement as fully bonded. The vessel model is pressurized using 20 incremental steps. Displacements, strains, stresses, using 20 incremental steps. Displacements, strains, stresses, concrete cracking and reinforcement yielding are observed at every step where appropriate. A final post-mortem is presented.

THE THREE-DIMENSIONAL BOND-LINKAGE ELEMENT

The three-dimensional bond-linkage element, has been developed to model the reinforcement of concrete which is represented by a 3D-4 nodded line element attached to a bond linkage element. This development connects the line and the solid elements together and has two nodes (Fig. 1). This element was first developed in a two dimensional form by Bresler & Scordelis (1964) and was later used by others (Al-Obaid 1992; Bazant & Bhat 1976; Bazant & Oh 1983; Brading & Hills 1986). In this work, the element is extended to three dimensions. Physically, the element does not exist, but its mechanical action is represented by three orthogonal springs connected in the horizontal, vertical and lateral directions to steel and concrete elements. The horizontal spring represents the bond stiffness and acts as a bond

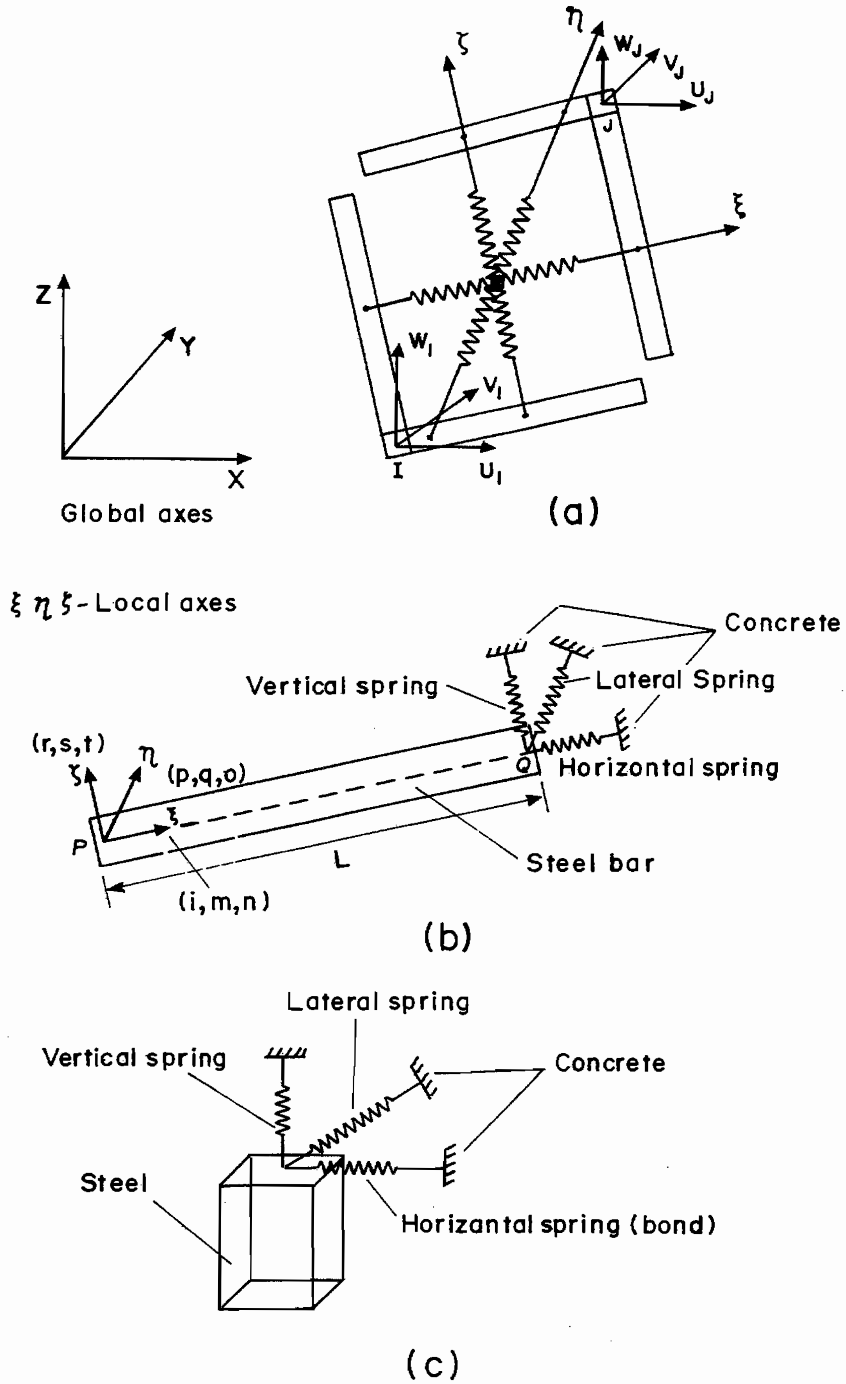


Fig. 1. Three-dimensional bond-linkage element. (a) Bond-linkage element; (b) Direction cosines; (c) Bond representation.

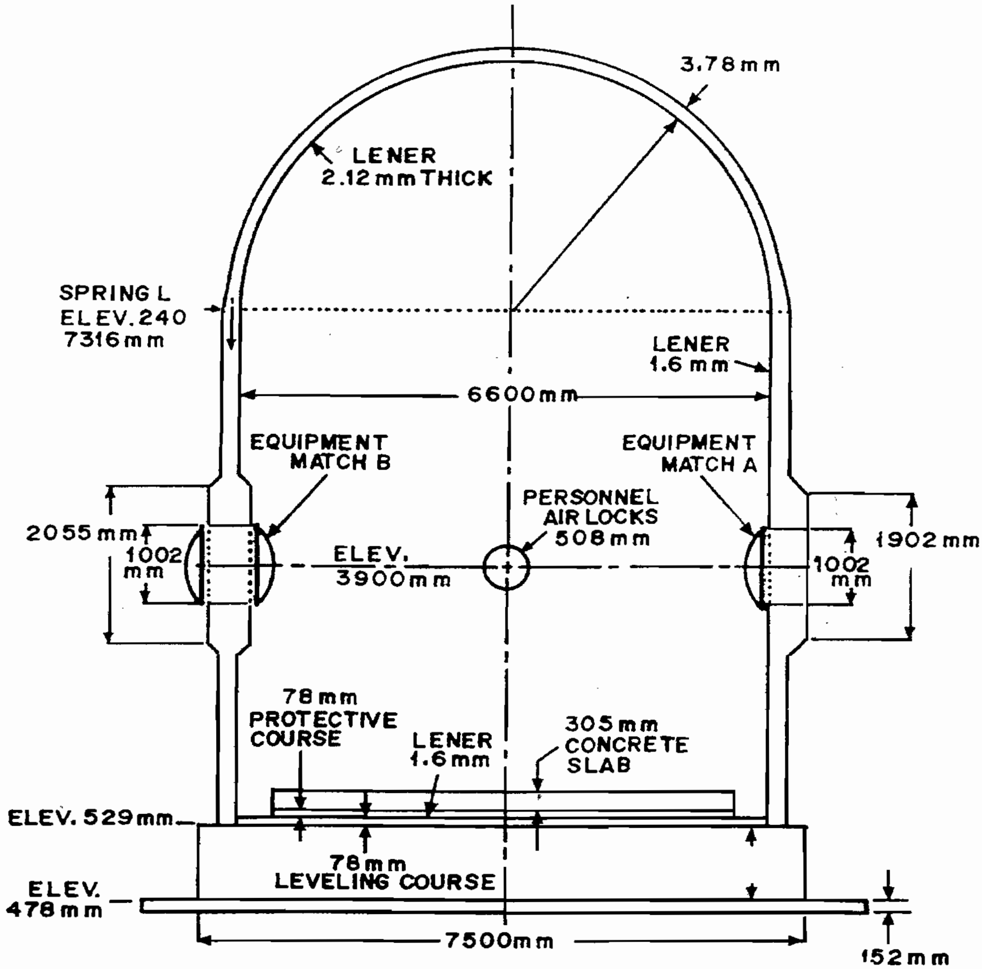


Fig. 2. Schematic presentation of the 1 : 6 scale reinforced concrete containment model.

between the steel and concrete. The other two springs represent the vertical and the lateral adhesion between the steel and concrete (Fig. 2). The procedure for the derivation of stiffness matrix and computation of stresses is given below.

Let X, Y, Z, and ξ, η, ζ, be the global and the local co-ordinate systems (Fig. 1a, b, c), respectively. The direction cosines of the local axes with respect to global axes (ξ, η, ζ) are (l, m, n), (p, q, o) and (r, s, t). Let P, Q be the line element nodes. The direction cosines in terms of nodal co-ordinates may be written as:

$$l = \frac{X_Q - X_p}{L}; \qquad m = \frac{Y_Q - Y_p}{L}; \qquad n = \frac{Z_Q - Z_p}{L} \tag{1}$$

$$p = \frac{-m}{\sqrt{1 - n^2}}; \qquad q = \frac{-1}{\sqrt{1 - n^2}} \tag{2}$$

$$r = \frac{-ln}{\sqrt{1 - n^2}}; \qquad s = \frac{-mn}{\sqrt{1 - n^2}} \tag{3}$$

in which

$$L = \sqrt{(X_Q - X_p)^2 + (Y_Q - Y_p)^2 + (Z_Q - Z_p)^2} \tag{4}$$

In the case of $l = m = 0$ and $n = 1$, the direction cosines take the following values:

$$p = 0; \quad q = 1; \quad t = 0; \quad r = -1; \quad s = 0 \tag{5}$$

With this definition for the direction cosines, the local ξ is always tangential to the line element, with the other two directions being orthogonal to it.

Let ΔS_b, ΔS_v, and ΔS_L be the incremental slips in the horizontal, vertical and lateral directions of the steel element. The incremental relationship between the slip and the nodal displacements can then be written as:

$$\begin{matrix} \Delta S_h \\ \Delta S_v \\ \Delta S_l \end{matrix} = \begin{bmatrix} -l, & -m, & -n, & l, & m, & n \\ -p, & -q, & 0, & p, & q, & 0 \\ -r, & -s, & -t, & r, & s, & t \end{bmatrix} \begin{Bmatrix} \Delta\delta_i \\ \Delta V_j \\ \Delta W_i \\ \Delta\delta_j \\ \Delta V_j \\ \Delta W_j \end{Bmatrix} \tag{6}$$

or

$$\Delta S^e = T\Delta\delta^e \tag{6a}$$

where T is the transformation matrix, $\Delta\delta^e$ are the global element displacements and i and j are the element nodes.

The local incremental bond stress and bond-slip may be written as:

$$\begin{Bmatrix} \Delta\sigma_h \\ \Delta\sigma_v \\ \Delta\sigma_t \end{Bmatrix} = \begin{bmatrix} E_h & 0 & 0 \\ 0 & E_v & 0 \\ 0 & 0 & E_t \end{bmatrix} \begin{Bmatrix} \Delta S_h \\ \Delta S_v \\ \Delta S_t \end{Bmatrix} \tag{7}$$

or

$$\Delta\sigma_b^e = E_b \Delta S^e \tag{7a}$$

where E_h, E_v and E_t are the bond-slip moduli in the three directions. These are obtained by using an idealized form of bond-slip curves. Here

$$E_h = \frac{\Delta\sigma_b}{\Delta S'} \tag{7b}$$

where $\Delta\sigma_b$, ΔS are the incremental bond stress and slip from a specified bond-slip curve.

Assuming bond stresses as average, along the length of the steel with length L, the incremental nodal force and the stress relation may be written in the following form:

$$\Delta P^e = \pi d L T^T \Delta\sigma_b^e, \tag{8}$$

where:

$\Delta\sigma_b^e = [\Delta\sigma_b, \Delta\sigma_v, \Delta\sigma_t]^T$

$\Delta P^e = [\Delta P_\delta^i, \Delta P_v^i, \Delta P_w^i, \Delta P_\delta^j, \Delta P_v^j, \Delta P_w^j]^T$

d = diameter of steel embedded in concrete

πdL = surface area over which the linkage element is connected with the steel.

Table 1. Bond-linkage stiffness matrix.

The explicit form of the bond-linkage stiffness is:

$$\underset{6\times 6}{K_b} = \begin{bmatrix} K_{b11} & K_{b12} \\ K_{b21} & K_{b22} \end{bmatrix}$$

where

$$K_{b12} = K_{b21} = -K_{b11}$$

$$K_{b22} = K_{b11}$$

$$\underset{3\times 3}{K_{b11}} = \begin{bmatrix} K_{b11} & K_{b12} & K_{b13} \\ & K_{b22} & K_{b22} \\ & & K_{b33} \end{bmatrix}$$

$$K_{b11} = \pi dL(l^2E_h + p^2E_v + r^2E_t)$$

$$K_{b22} = \pi dL(m^2E_h + q^2E_v + S^2E_t)$$

$$K_{b33} = \pi dL(n^2E_h + t^2E_v)$$

$$K_{b12} = \pi dL(lmE_h + pqE_v + rsE_t)$$

$$K_{b13} = \pi dL(lnE_h + rtE_v)$$

$$K_{b23} = \pi dL(mnE_h + stE_t)$$

$$\left.\begin{matrix} l, m, n \\ p, q, r \\ s, t \end{matrix}\right\} = \text{direction cosines}$$

$$\pi dL = \text{perimeter of the steel}$$

Now the relationship between the incremental nodal forces and the incremental displacements can be found by substituting Eqns. 6 & 7 in Eqn. 8:

$$\Delta P^e = \pi dLT^T E_b T \Delta\delta^e \tag{9}$$

$$\Delta P^e = K_b^e \Delta\delta^e, \tag{9a}$$

where

$$\underset{6\times 6}{K_b} = \pi dLT^T E_b T$$

$$\underset{6\times 6}{K_b} = \text{bond-linkage stiffness matrix.} \tag{9b}$$

The explicit form of K_b is given in Table 1.

The stresses in terms of nodal displacements can be calculated by substituting Eqn. 6a in Eqn. 7a as follows:

$$\Delta\sigma_b^e = E_b T \Delta\delta^e \tag{10}$$

CONSTITUTIVE RELATIONS FOR ENDOCHRONIC MODEL

Extensive work has been carried out by Bazant & Bhat (1976) on the basic incremental constitutive equations.

$$(dS_{ij} + \delta_{ij} d\sigma_m) + (dS_{ij}^P + \delta_{ij} d\sigma_m) = 2Gd\epsilon_{ij} + 3Kd\epsilon_m\delta_{ij} \tag{11}$$

The strain increment $d\epsilon_{ij}$ is defined in terms of intrinsic time increment

$$dz = dn/z_1F_2\left[1+\frac{\beta_1 n+\beta_2 n^2}{1+F_1a_7}\right] \tag{12}$$

where $n_1 z_1 \beta_1 \beta_2$ and a_7 are coefficients. The volumetric strain increment is

$$\epsilon_m = \frac{d\sigma_m}{3K} + d\lambda \tag{13}$$

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

$$\lambda = \Sigma d\lambda \tag{14}$$

The incremental stresses are computed for up to plastic conditions as

$$d\sigma_{ij} + d\sigma_{ij}^P = 2Gd\epsilon_{ij} + (3K-2G)\delta_{ij}d\epsilon_m \tag{15}$$

The stress strain relation in a matrix form is given as

$$\begin{Bmatrix} \Delta\sigma_x + \Delta\sigma_x^P \\ \Delta\sigma_y + \Delta\sigma_y^P \\ \Delta\sigma_z + \Delta\sigma_z^P \\ \Delta\tau_{xy} + \Delta\tau_{xy}^P \\ \Delta\tau_{yz} + \Delta\tau_{yz}^P \\ \Delta\tau_{zx} + \Delta\tau_{zx}^P \end{Bmatrix} = \begin{bmatrix} (K+\frac{4}{3}G)(K-\frac{2}{3})(K-\frac{2G}{3}) & 0 & 0 & 0 \\ (K+\frac{4}{3}G)(K-\frac{2}{3}G) & 0 & 0 & 0 \\ (K+\frac{4}{3}G) & 0 & 0 & 0 \\ & \beta' G & 0 & 0 \\ & & \beta' G & 0 \\ & & & \beta' G \end{bmatrix} \begin{Bmatrix} \Delta\epsilon_x \\ \Delta\epsilon_y \\ \Delta\epsilon_z \\ \Delta Y_{xy} \\ \Delta Y_{yz} \\ \Delta Y_{zx} \end{Bmatrix} \tag{16}$$

where

$$\{\Delta\sigma_p\} = S_{ij}\, dZ + \delta_{ij} 3K\, d\lambda \tag{16a}$$

and K, G and β' are moduli and aggregate interlocking parameters. The material matrix D^* is constant modified to reflect the reduced stiffness across the crack, for example, where one crack normal to X^* direction occurs, the concrete is assumed not to resist any tensile stress in that direction. A brief outline is presented later on for the non-linear steps taken in the finite element analysis. The non-linear bond-linkage element is included to assume that the 1:6 model is fully bonded. Since it is a reinforced concrete model it is imperative not to ignore the bond between the reinforcement and model concrete. The stiffness matrix (K) is evaluated as

$$[K] = \int_{-1}^{+1}\int_{-1}^{+1}\int_{-1}^{+1} [B]^T[D^*][B]d[J]\, d\xi\, d\eta\, d\zeta$$

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 Eqn. 16.

$$\Delta\sigma^* + \Delta\sigma^{P^*} = D_T^* \cdot \Delta\epsilon^* \tag{17}$$

Where one crack normal to X^* direction occurs, the concrete is assumed to resist no tensile stress in that direction; hence

$$\begin{aligned} &\sigma_x^* = 0 \\ &D_{11} = \Delta\epsilon_x^* + D_{12}\Delta\epsilon_y^* + D_{13}\Delta\epsilon_z^* = \Delta\sigma_x^{P^*} \\ &\Delta\sigma^* = \Delta\sigma^{P^*} - D_{12}/\Delta\epsilon_y^* - D_{13}/\Delta\epsilon_y^* \\ &\Delta\epsilon_x^* = \Delta\sigma_x^{P^*}/D_{11} - D_{12}/D_{11}\cdot(\Delta\epsilon_y^*) - D_{13}/D_{11}\cdot(\Delta\epsilon_y^*) \end{aligned} \tag{18}$$

Upon substituting Eqn. 18 within the second and third rows of Eqn. 17 and rearranging the terms in D_T^*; the following are obtained:

$$\Delta\sigma_y^* + \Delta\sigma_y^{P^*} - D_{12}/D_{11}\Delta\sigma_x^{P^*} = \left(D_{22} - \frac{D_{21}D_{12}}{D_{11}}\right)\Delta\epsilon_y^* + \left(D_{23} - \frac{D_{12}D_{13}}{D_{11}}\right)\Delta\epsilon_z^*$$

$$\Delta\sigma_z + \Delta\sigma_z^{P^*} - D_{13}/D_{11}\Delta\sigma_x^{P^*} = \left(D_{23} - \frac{D_{12}D_{13}}{D_{11}}\right)\Delta\epsilon_y^* + \left(D_{33} - \frac{D_{13}D_{31}}{D_{11}}\right)\Delta\epsilon_z^*$$

$$\Delta\tau_{xy} + \Delta\tau_{xy}^{P^*} - \beta D_{44}\Upsilon_{xy}^*; \qquad \Delta\tau_{yz}^* + \Delta\tau_{yz}^{P^*} = D_{55}\Delta\Upsilon_{yz}^*;$$

$$\Delta\tau_{zx} + \Delta\tau_{zx}^{P^*} = \beta D_{66}\Delta\Upsilon_{zx} \tag{19}$$

Equation 19 is referred to a local (crack) coordinate system. It is then transformed in the global coordinate system.

If there are two cracks at one point (denoted X^* and Y^*) and both cracks are open, then the D^* 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^* is given by:

$$[D_T^*] = 0$$

STEP-BY-STEP NON-LINEAR FINITE ELEMENT ANALYSIS

1. Apply a load increment ΔP_n where n is the load increment. Accumulate total load $P_n = P_{n-1} + \Delta P_n$, and $R = \Delta P_n$, where R is the residual load vector.

$$\Delta P_n = K_B\Delta\delta = (\pi dLT^T E_B^T)\Delta\delta_n$$

2. Solve $\Delta\delta_i = K^{-1}R$, where i is the iteration number and K_T is the stiffness matrix of the structure.

   Accumulate total displacements:

$$\delta_i = \delta_{i-1} + \Delta\delta_i \text{ where } \Delta\delta_i = \Delta S_i \cdot T^{-1}$$

   Total slip "i", S_i becomes

$$S_i = S_{i-1} + \Delta S_i$$

Table 2. Step-by-step crack investigation.

Crack indicators NCK[1], NCK[2], NCK[3]

NCK 1 Crack normal to the principal stress 1

NCK 2 Crack normal to the principal stress 2

NCK 3 Crack normal to the principal stress 3

NCK[1] = 0, NCK[2] = 0, NCK[3] = 0 } - No Cracks

NCK[1] = 1, NCK[2] = 1, NCK[3] = 1 } - Cracks Open

NCK[1] = 2, NCK[2] = 2, NCK[3] = 2 } - Cracks Closed

σ, ε	stress/strain, state at integration point
ε_i	principal strains
σ_i	principal stresses; i − 1, 2, 3
σ_t	limiting tensile strength of concrete
T_ε, T_σ	transformation matrix

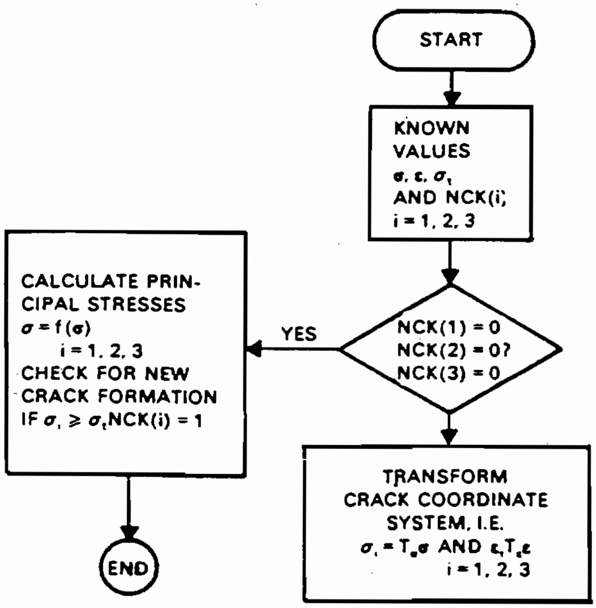
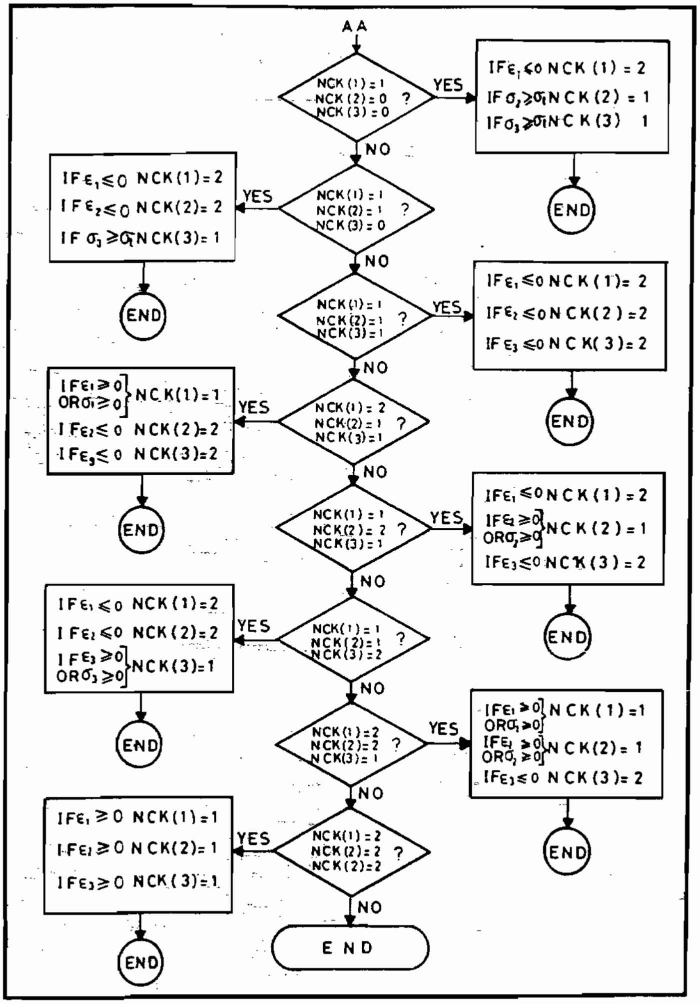


Table 2. (Continued).



CRACK IN PRINCIPAL DIRECTIONS THREE AND ONE

$$D^*_{11} = D^*_{33} = D^*_{12} = D^*_{21} = 0$$

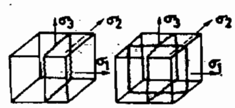
$$D^*_{13} = D^*_{31} = D^*_{23} = D^*_{31} = 0$$

$$D^*_{22} = D_{22} - D_{12}\frac{D_{12}}{D_{11}} - D_{23}\frac{D_{23}}{D_{33}}$$

$$D^*_{44} = \beta D_{44}$$

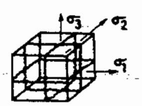
$$D^*_{55} = \beta D_{55}$$

$$D^*_{66} = \beta D_{66}$$



CRACKS IN ALL THREE PRINCIPAL DIRECTIONS

$$[D^*] = [0]$$



3. For each element type calculate strain increments

$$\Delta\epsilon_i = B\Delta\delta_i$$

and strains $\epsilon_i = \epsilon_{i-1} + \Delta\epsilon_i$.

4. For each element type

$$\Delta\sigma_i = f(\sigma)\Delta E$$

$$\Delta\sigma_{bi} = E_b(\sigma_{bi-1})\Delta S_i$$

where

$$E_b = \begin{bmatrix} E_h & 0 & 9 \\ 0 & E_v & 0 \\ 0 & 0 & E_l \end{bmatrix}$$

Accumulate stresses

$$\sigma_{bi} = \sigma_{bi-1} + \Delta\sigma_{bi}$$

5. Check the state of bond

If $|S_i| > S_{\max}$ Bond is broken

If $|S_i| > S_{\max}$ Bond stresses are computed

The correct stress is $\sigma_{bi} = \sigma_{bi} - \Delta\sigma_D$.

6. The total stresses are converted into equivalent loads as

$$\int_v B^T \sigma_i dvol = \int B^T \sigma d[J]\, d\xi\eta\, d\zeta$$

7. The total internal equivalent loads and residuals are written as

$$P_{int} = \pi dLT^T \sigma_{bi}$$

$$R = P_n - \int_v B^T \sigma d|J|\, d\xi\, d\eta\, d\zeta$$

For cracking Table 2 is referred to.

8. The Bond-linkage stiffness matrix is written as:

$$K_b = \pi dLT^T E_b^T$$

(see table 1).

Based on the crack model given (Al-Obaid 1990) for Endochronic failure model, Table 2 gives a step-by-step layout of the crack propagation under incremental pressure.

APPLICATION TO VESSEL

The Oldburg containment vessel of 1 : 6 scale parameters is chosen. Figures 3 & 4 give the model parameters and the finite element mesh. The results of this analysis are given briefly in Fig. 5, and are plotted along with results obtained by other researchers (Hardingham *et al.* 1967, Brading & Hills 1986, Nilson 1968, Campbell-Allen & Low 1968). The safety factor against the design computed to be 2.75 based on the loss of bond, excessive cracking and the rupture of reinforcement.

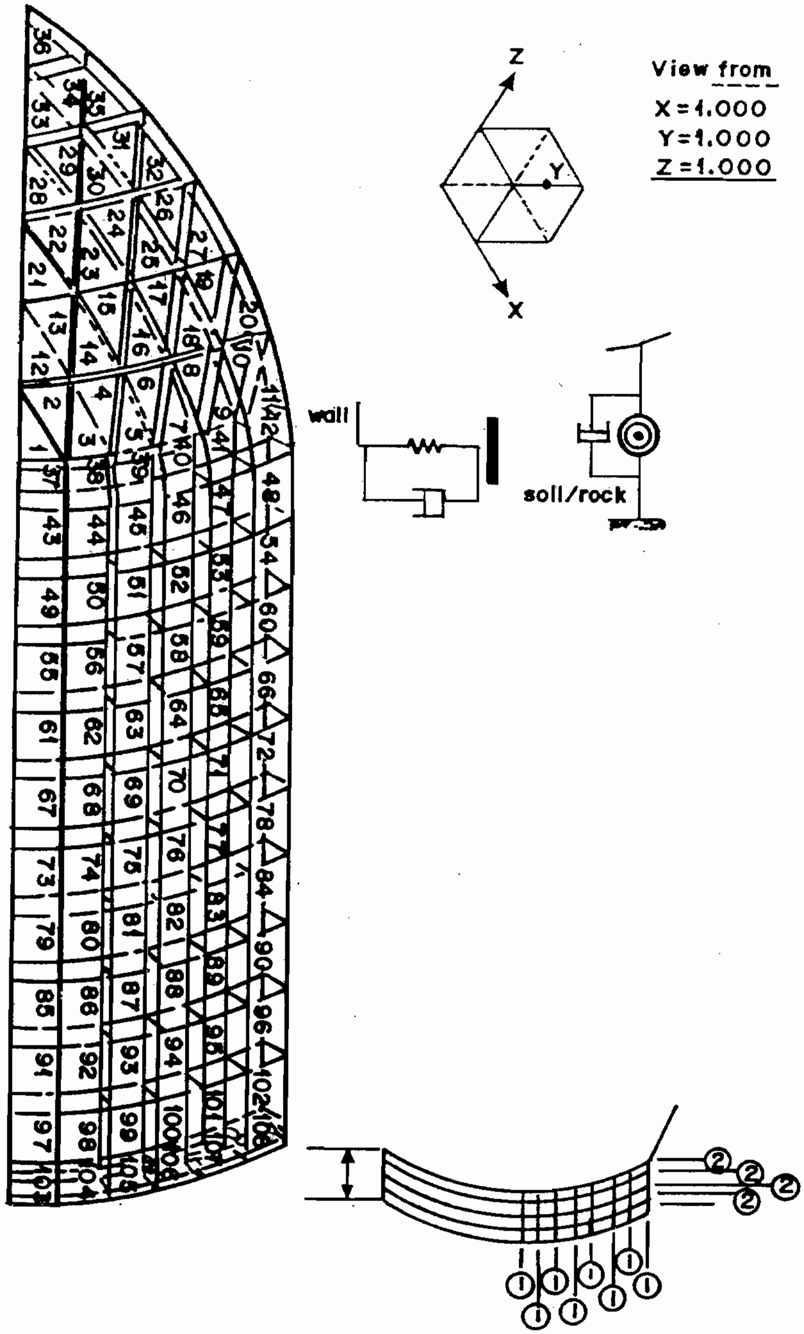


Fig. 3. 1 : 6 model finite element mesh.

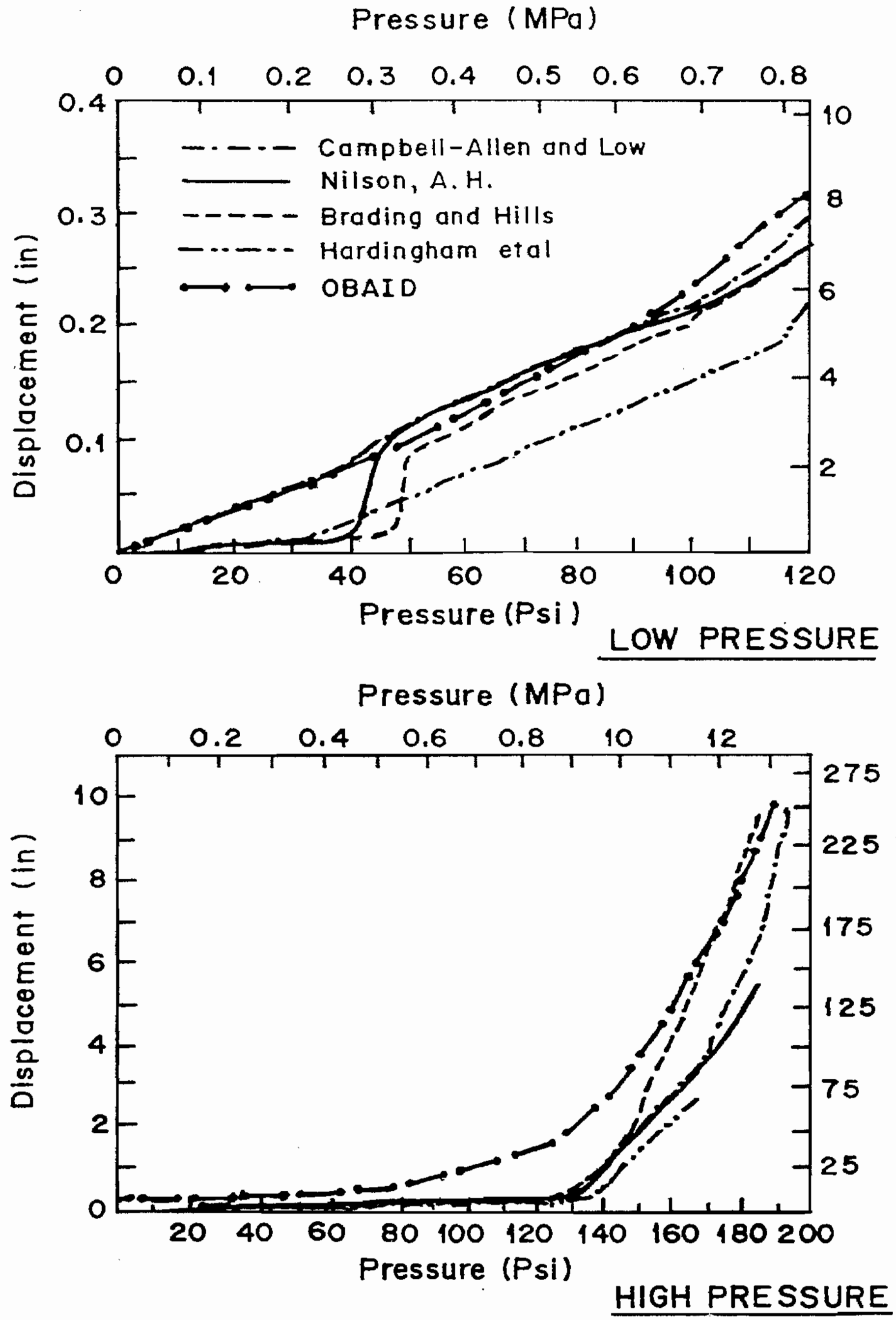


Fig. 4. Radial displacements at mid height of the wall.

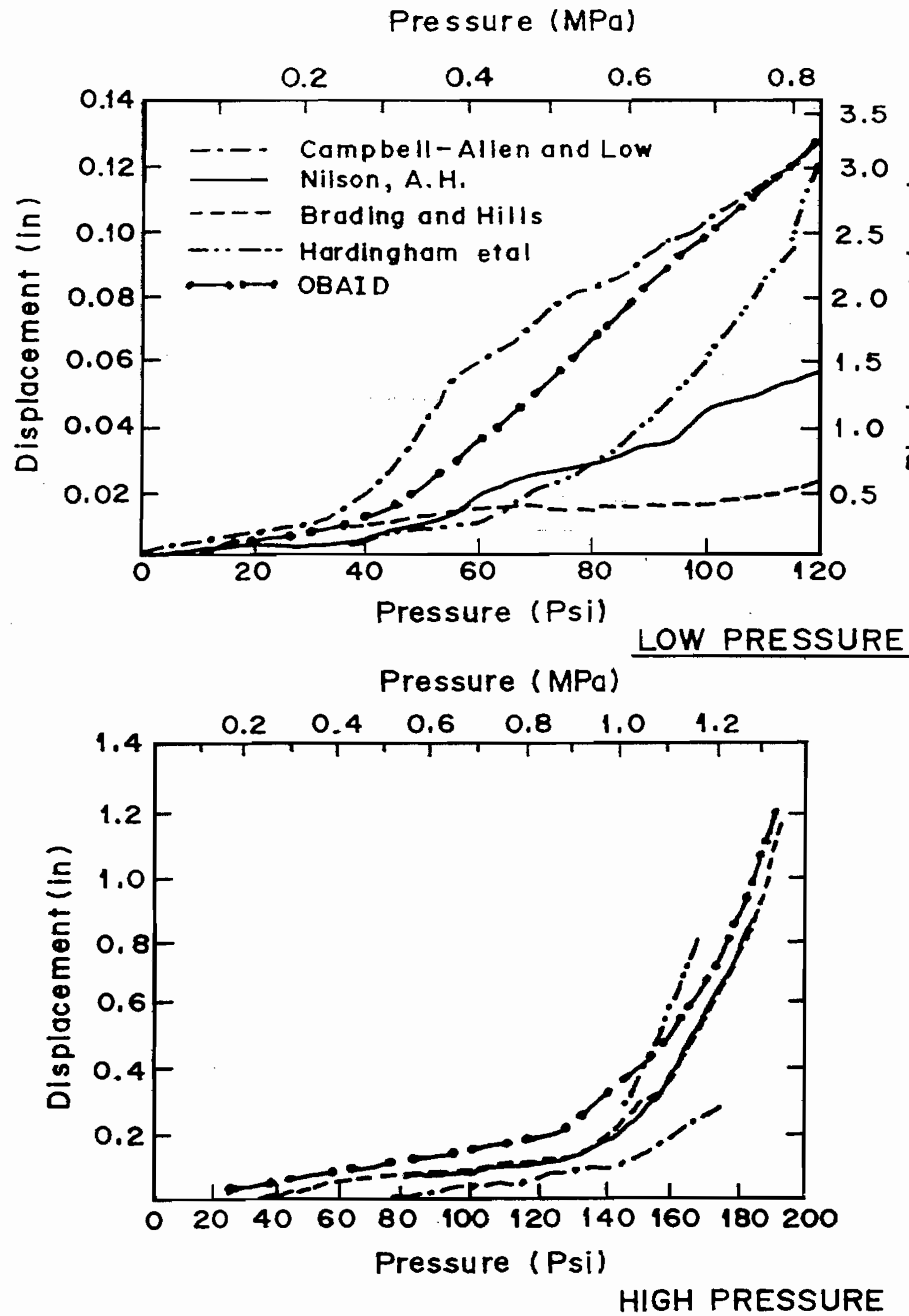


Fig. 5. Vertical displacements at mid height of the wall.

The Endochronic Theory adopted in the over pressurization of the 1 : 6 containment model, gives results which are in agreement and disagreement in certain areas with other approaches. Further research is needed to see how the test results are compared. Since the Endochronic model has been tested in other cases, the author is convinced that this analysis is more valid owing to its true representation of constitutive elements.

The Endochronic model represents the best available model for nonlinear triaxial behaviour of a heavily reinforced structure such as the one analyzed above. However the best model for lightly reinforced structures now appears to be the microplane model (Bazant & Ozbolt 1990).

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التحليل المسبق للأوعية الإحتوائية الخرسانية
ذات الضغط العالي
باستخدام نموذج اندوكرنك Endochronic

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خلاصة

يتناول هذا البحث بداية تحليل خطوات سير الشروخ المتواصلة باستخدام عناصر التحليل ذات الأبعاد الثلاثة وهي عناصر Isoparametric وعناصر Bond-Linkage. وقد تم استخدام نموذج اندوكرنك Endochronic الذي يأخذ في الإعتبار المتغيرات اللدنة والغير اللدنة، وتم تطبيق هذا النموذج على وعاء اولدبرج Oldburg. ولقد تم تعديل نموذج اندوكرنك وربطه بنماذج تحليل الشروخ في برنامج الحاسب الآلي OBAID لأعطاء النتائج اللازمة تحت ظروف الضغط العالي والمنخفض، ثم مقارنة نتائج التحليل مع نتائج أخرى.