RECENT DEVELOPMENTS IN THE FINITE ELEMENT ANALYSIS OF PRESTRESSED CONCRETE REACTOR VESSELS

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SUMMARY

This paper describes recent developments of the finite element method as applied to linear and non-linear problems in pressure vessel analysis.

In the first part of the paper, the SBB finite element program for the analysis of PCRV is briefly summarized (Forschungsvorhaben Spannbeton-Reaktordruckbehälter), with particular reference to advances in finite element modelling techniques. The capabilities of the program are illustrated with the example of a three-dimensional substructure analysis of standpipe penetrations and their interaction with the global behaviour of the containment which is in our case the THTR 1:5 scale Model. Thereafter, results of a parameter study on a "reference vessel" are presented in which the influence of material properties is investigated in regard to response of the structure.

In the second part of the paper, the effects of material non-linearities are dealt within the context of time dependent and time independent phenomena. Five different algorithms are briefly described for numerical solution of the non-linear problems. Limitations and shortcomings of these different methods are illustrated with the analysis of crack-propagation in an axisymmetric PCRV. Another investigation deals with two different concepts to characterize non-linear deformation behaviour within the frame of non-linear elasticity or elastoplasticity. The effects of the different formulations are shown on the example of a reinforced disc exhibiting cracking and non-linear deformation behaviour under lateral loading. Then the validity of some assumptions for the analysis of creep are reviewed with reference to the concepts of viscoelasticity and viscoplasticity. This critical appraisal is followed by a discussion on the numerical restrictions of the ensuing time-marching algorithms which arise due to the form of creep law used. These effects are then illustrated on the example of an axisymmetric PCRV. In conclusion, the formulations for creep, cracking and non-linear deformation behaviour are combined for the analysis of a standpipe penetration zone subjected to transient pressure and temperature cycles.

In the third part of the paper the computation of mode shapes and frequencies is briefly reviewed for the eigensolution of large scale problems. In essence, two techniques are compared for the eigencomputation of out-of-core matrices. The direct method involves static condensation and a finite number of similarity transformations for "hyper-tridiagonalisation" of the dynamic matrix. The iterative scheme operates directly on the original dynamic system iterating on vector subspaces which embed the desired eigenvectors. In conclusion, these two techniques are applied to the eigensolution of a complex PCRV for comparison of their computational merits.

1. Introduction

The following discussion is intended as an introduction to the main theme of our presentation at the Berlin Reactor Conference, September 1973. This forthcoming lecture will cover exclusively quasistatic non-linear phenomena. Within this context six numerical schemes are to be presented and will cover different material formulations of non-linearities due to fracture and non-linear deformation behaviour in the pre- and post failure range. In addition, various specifications of multiaxial creep under loading and unloading are to be discussed. A special study on the influence of memory effects in transient creep regimes will conclude the investigation of PCRVS.

Given the space limitations imposed on the present write-up it was considered necessary to restrict our current account to some linear aspects of the finite element analysis of PCRVS. In particular, we refer to a special purpose program now under development and primarily intended for the linear and non-linear study of reinforced and prestressed concrete components under composite action in a reactor environment. However, its application to other composite structures in civil and mechanical engineering, made up of solid components reinforced by cables and membranes and exhibiting cracking, creep, plasticity and related non-linear phenomena of quasistatic nature is evident.

The program is subdivided into three parts: linear elastostatic phase, non-linear quasistatic phase and non-linear diffusion phase for transient regimes. The program may be considered a special version of the general purpose program ASKA [1]. It features most of the basic capabilities of ASKA, such as substructuring, providing also a user-oriented input with a number of mesh generators to aid the preparation of topology, nodal and element data. The output includes display and plotting facilities utilizing interactive computer graphics [2]. At present, the first part has been completed and is available with a well defined interface to external users [3]. A number of studies are presently conducted to accumulate experience in the areas of fracture, non-linear deformation behaviour (elasticity and plasticity) and creep (viscoelasticity and viscoplasticity) before defining restrictive interfaces for external users. For the third part, development of a general non-linear diffusion capability for the associated analysis of heat and moisture migration within composite solids is in progress.

2. Basic Concepts in Finite Element Analysis

The versatility of the finite element method requires no commentary and is best demonstrated by the all too numerous publications in this field. Here we merely attempt to summarize some of the latest developments in the modelling process of different structural components of PCRVS. For details of the underlying theory and program concepts we refer the reader to the extensive studies in [3] and [1], [5], [6].

2.1 Element Configurations for the Analysis of PCRVS.

Figure 1 shows line, surface and solid elements which are applicable to two- and three-dimensional analysis. The curved hexahedral and pentahedral elements HEXEC 27 and PENTAC 18 are intended for idealisation of concrete components; the curved triangular and quadrilateral membrane elements TRIMC 6 and QUAMC 9 model the liner behaviour or smeared reinforcement layers; the curved rod element FLAC 3 accounts for discrete prestressing cables or reinforcement bars; the elastic linkage element LINK simulates differential slippage between structural components e.g. due to partial bond. It is obvious that the plane

stress elements TRIMC 6 and QUAMC 9 can also be used for the analysis of prismatic solids introducing plane strain assumptions. $H^{1/1}x$

Figure 2 shows analogous line, surface and solid elements which are available for axisymmetric analysis. In particular, the curved triangular and quadrilateral ring elements TRIAXC 6 and QUAXC 9 are suited for the idealisation of concrete components; the curved membrane shell element FLAXC 3 accounts for the liner or smeared reinforcement layers. Circumferential prestressing cables may be modelled with the ring type element RINGX, an element with a single node exhibiting stiffness in the radial direction only; partial bond can be simulated with the axisymmetric linkage element LINKX.

All elements are based on a uniform concept which specifies the input and output data consistently at each element node. In particular, coordinates x , elastic moduli E , thicknesses t , distributed volume or surface loads $\bar{p}_v$, $\bar{p}_a$ and prescribed initial strains η are given at each element node. At the same time displacements u , strains γ and stresses σ are also output at each element node. Once all nodal data are known the spatial variation of all variables may be derived via the initially selected interpolation functions.

2.2 Interpolation Functions

We recall that the choice of interpolation functions ω is restricted by two considerations necessary to ensure convergence and boundedness of the solution :

1. Completeness requirements.
2. Inter-element continuity requirements.

Completeness is satisfied if the polynomial expansions, which are suited best for numerical work, contain all first order terms (the order of differentiation in the strain energy expression is in our case $m = 1$). This requires that the modal functions satisfy the following condition at each point of the element domain

$$\sum_{i=1}^n \omega_i(\xi) = 1 \quad (1)$$

In addition, the geometric approximation must be a subset of the displacement expansion to represent all constant energy states within the element

$$\omega_x(f) = \omega_u(f) \quad (2)$$

The continuity requirements before and after deformation are satisfied if both, geometric and displacement interpolation are of the same order in contiguous elements a, b

$$\begin{aligned} \omega_x^a(f) &= \omega_x^b(f) \\ \omega_u^a(f) &= \omega_u^b(f) \end{aligned} \quad (3)$$

The old question of the higher order versus lower order elements has been answered, at least partially, in favour of the higher order expansions [7]. The discretisation error depends mainly on the element subdivision R , the order of polynomial expansion p and the order of differentiation m . The energy norm is then a measure for the discretisation error

$$\|u - \hat{u}\|_e = c_p R^{2(p+1-m)} \quad (4)$$

where C_1 denotes a proportionality factor. In contrast, the numerical error due to round off and initial truncation is hardly affected by the order of polynomial expansion p and depends mainly on the spectral conditioning number for the inversion [6]

$$\text{cond } K = \lambda_{\max} / \lambda_{\min} \sim c_2 h^{-2m} \quad (5)$$

Here $\lambda_{\max}, \lambda_{\min}$ denote the extreme eigenvalues of K , which increase mainly with the number of degrees of freedom. This clearly indicates that the accuracy is improved much more effectively with the order of expansion rather than by the refinement of the mesh size. A word of caution should be appended to this discussion. It is straightforward to construct examples for which a TRIM 3 idealisation would be more effective than a TRIM 6 one. However, the main theme of our above assertion remains, in general, correct.

In what follows we consider polynomial expansions of the Lagrangean type for which only function values, but not their derivatives are used as nodal quantities. The discussion is restricted to triangular and quadrilateral elements of our program and uses for convenience cartesian coordinates instead of the more effective and elegant parametric representation in homogeneous coordinates.

Triangular elements of the TRIM-type have the marked advantage that the modal functions are expressible by complete polynomials [8], [9]. This implies that the functional variation in the element domain is independent of linear coordinate-transformations ensuring "isotropic" properties of the expansion

Quadrilateral elements of the QUAM-type are in contrast based on modal functions which are products of one-dimensional Lagrangean interpolation schemes [10], [11]. These expansions contain complete polynomials of the order p but also include higher order terms up to the order $2p$. This implies that the functional variation in the element domain depends strongly on linear coordinate transformations losing the "isotropic" properties of the expansion

QUAM4
QUAM9
QUAM16

$P=1$

$P=2$

$P=3$

The convergence properties of these elements are demonstrated below on a simple example. Figure 3 shows the input data and a typical idealisation for a cantilever beam under tipload which has been previously used for similar investigations. The theoretical solution [12] provides an upper bound as it accounts for shear warping which is not suppressed at the built-in end. Figure 4 illustrates the relative error of tip deflections for different element configurations as function of the number of unknowns. We observe monotonic convergence and the marked improvement achieved with elements of higher order as compared to the lower order ones for the same number of degrees of freedom. As to be expected, the bilinear quadrilateral QUAM4 yields far better convergence than the constant strain triangle TRIM3, since it contains the xy term. On the other hand, this is not a fair appraisal since TRIM3 was never intended for beam webs subject to bending. In comparing triangular and quadrilateral elements of higher order we note that the anisotropy of quadrilaterals yields desirable effects in the case of prismatic structures. On the other hand, triangles appear less sensitive than quadrilaterals in respect to high Poisson's ratios. A similar effect can be observed with geometric distortions due to non-linear mappings between the global space x and the parameter space ξ , which is normally used to describe the element geometry.

A word of caution is appropriate with regard to these geometric distortions. For simplicity let us consider a one-dimensional line-element whose geometry and displacements are defined by polynomial expansions of the order q and p in the homogeneous coordinates ξ

$$\begin{aligned} x &= x(\xi^q) \\ u &= u(\xi^p) \end{aligned} \quad (6)$$

Inversion of the mapping between the global space x and the parameter space ξ yields the following approximation for the displacements

$$\begin{aligned} \xi &\rightarrow \xi(x^{1/q}) \\ u &= u(x^{p/q}) \end{aligned} \quad (7)$$

This clearly indicates that the geometric representation is primarily improved at the expense of the displacement approximation in the global space of analysis. This fact suggests the use of subparametric elements in which the geometry is represented by linear interpolation $q=1$. We then conclude that the case of $p=q$ should be applied in a manner ensuring the best possible centering of the midside and

interior nodes in order to reduce geometric distortions.

2.3 Quadratic Interpolation

All elements shown in Figs. 1 and 2 are based on quadratic interpolation of the position vector $\mathbf{x}$, displacements $\mathbf{u}$ and prescribed distributed loads $\bar{\mathbf{p}}$

$$\begin{aligned} \text{Quadratic} \quad \mathbf{x} &= \omega_{\mathbf{x}} \mathbf{x}_I = \omega^{\mathbf{x}} \mathbf{x}_I \\ \text{Interpolation} \quad \mathbf{u} &= \omega_{\mathbf{u}} \mathbf{u}_I = \omega^{\mathbf{u}} \mathbf{u}_I \\ \mathbf{p} &= \omega_{\mathbf{p}} \mathbf{p}_I = \omega^{\mathbf{p}} \mathbf{p}_I \end{aligned} \quad (8)$$

$\omega^{\mathbf{I}}$ denotes the second order polynomial expansion with $\mathbf{x}_I$, $\mathbf{u}_I$ and $\mathbf{p}_I$ as the relevant nodal vectors.

2.4 Multilinear Interpolation and Extrapolation

Besides position vector and displacement field the element variation needs to be specified for the initial strains η , material properties $\mathbf{E}$ and membrane thicknesses $\mathbf{t}$. For this purpose quadratic interpolation cannot be used as it might distort these field variables into the negative range, in spite of the fact that all nodal values are positive. Therefore, multi-linear interpolation over subregions is applied within each element defining the state values for η , $\mathbf{E}$ and $\mathbf{t}$ at each pivot of the numerical integration scheme. For example, Fig. 5 illustrates the four subregions for a triangular and quadrilateral element within each of which the state variables are interpolated linearly using $\omega^{\mathbf{I}}$ from the nodal intensities η_I , $\mathbf{E}_I$ and $\mathbf{t}_I$

$$\begin{aligned} \text{Multi-linear} \quad \mathbf{E} &= \omega_{\mathbf{E}} \mathbf{E}_I = \omega^{\mathbf{E}} \mathbf{E}_I \\ \text{Interpolation} \quad \eta &= \omega_{\eta} \eta_I = \omega^{\eta} \eta_I \\ \mathbf{t} &= \omega_{\mathbf{t}} \mathbf{t}_I = \omega^{\mathbf{t}} \mathbf{t}_I \end{aligned} \quad (9)$$

The opposite scheme is used to evaluate element nodal stresses in order to minimize distortional effects due to non-linear mappings of the element geometry. Figure 6 shows the pivot points of numerical integration where the stresses are first evaluated and are then extrapolated towards the nodes using a similar multi-linear technique over each subregion

$$\begin{aligned} \text{Multi-linear} \quad \sigma_{\text{PIV}} &= \mathbf{E} \boldsymbol{\varepsilon} = \mathbf{E} (\boldsymbol{\gamma} - \boldsymbol{\eta}) \\ \text{Extrapolation} \quad \sigma_{\text{NOD}} &= \omega^{-\mathbf{I}} \sigma_{\text{PIV}} \end{aligned} \quad (10)$$

The example of a square sheet under bilinear temperature gradient exhibits some effects of this extrapolation technique, see also [13]. Figure 7 defines the input data of this problem which should yield zero stress resultants for the boundary conditions shown. Figure 8 describes the idealisation with highly distorted triangular and quadrilateral elements TRIMC 6 and QUAMC 9 and gives the resulting internal strain energy. It is clearly seen that both element types are incapable of reproducing linear strain states due to non-linear mappings which appear to affect the quadrilateral more than the triangle. Figure 9 illustrates the effect of

extrapolation on the evaluation of nodal stresses when compared with the direct determination which is normally used. Both, average nodal values of the maximum principal stress and individual element contributions to the center node are given for the triangular TRIMC 6 idealisation. Figure 10 shows the analogous results for the quadrilateral idealisation using QUAMC 9. Both solutions clearly demonstrate the superior nodal stress representation of the multi-linear extrapolation scheme as against that obtained from direct evaluation.

We conclude that the multi-linear interpolation and extrapolation form a very satisfactory compromise between the traditional praxis-oriented "nodal" philosophy and the "pivot" point of view which considers the evaluation of stresses and internal work exclusively at the points of numerical integration.

3. Analysis of the THTR 1:5 Scale Model

This section demonstrates some of the program capabilities on a realistic example of complex nature concerned with the analysis of the THTR 1:5 scale model. The analysis is performed for three stages, an axisymmetric state, a three-dimensional state extending over a 30° wedge of the vessel and a detailed investigation of the standpipe penetration zone.

Figure 11 shows an isometric view of the PCRV which has been constructed by the firms HRB, Mannheim, and FKU, Essen, as a 1:5 scale model of the THTR 300 MW reactor, Schmehausen. It displays most of the details of the actual reactor which could hardly pose more difficulties for the analysis. Figure 12 illustrates the arrangement of vertical and horizontal prestressing cables, each layer being rotated by a 90° angle which implies from the start an absence of symmetry.

3.1 Axisymmetric Phase

By now axisymmetric investigations are standard practice in the field of pressure vessel analysis. We present here some results to illustrate the effects of penetrations and other irregularities in the circumferential direction and compare them with corresponding three-dimensional solutions.

Figure 13 shows the finite element idealisation of different structural components in the upper half of the vessel assuming a plane of symmetry at mid-height; 103 curved triangular and quadrilateral solid elements TRIAXC 6 and QUAXC 9 were used for representation of the concrete material; the action of the steel liner, the reinforcement and vertical cables were described by 43 curved membrane elements FLAXC 3 and the hoop cables were idealised with 56 RINGX elements, which are single node elements with stiffness in the radial direction only; altogether, 784 degrees of freedom were required for the total assembly.

Figures 15, 16 and 17 present the resulting stress contours for an internal pressure of $p_i = 30 \text{ kp/cm}^2$ and compare them with some solutions from three-dimensional analyses.

3.2 Three-dimensional Phase

A detailed three-dimensional analysis was performed to investigate the effects of penetrations on the overall vessel behaviour as well as the standpipe penetration zone.

Figure 14 illustrates the idealisation of a 30° wedge subdivided into seven substructures. For clarity the steel components are omitted in this figure. The mesh was highly refined in the perforated cap zone in order to accommodate all control rod penetrations. The concrete was represented by 669 curved hexahedron and pentahedron HEXEC 27 and PENTAC 18; the liner and the reinforcement of the penetrations were

idealised with 395 QUAMC 9 and TRIMC 6 curved membrane elements; the prestressing cables were described by 248 FLAC 3 elements, all of which were assembled using 16214 degrees of freedom. More detailed specifications of this analysis are given in [14].

Figures 15, 16 and 17 display the resulting stress contours for an internal pressure of $p_i = 30 \text{ kp/cm}^2$. The contourlines are plotted at two meridional sections right across the main penetrations ($\theta = 180^\circ$) and between them ($\theta = 210^\circ$). The results at the section $\theta = 210^\circ$ are compared with axisymmetric computations and indicate satisfactory agreement.

3.3 Perforated Cap Zone

The THTR 1:5 scale model contains 55 control rod and 36 reflector rod penetrations in the cap zone. Figure 18 indicates the arrangement of perforations within the 30° wedge, together with the idealisation of the three-dimensional phase. In the following we distinguish between centric and eccentric penetrations depending on their position with regard to the axis of rotation z .

Figure 19 shows the axisymmetric and three-dimensional mesh-layout used for a detailed investigation of a centric and an eccentric penetration. The vicinity of perforation is loaded on one side by prescribed displacements obtained from previous global computations and on the other side by the internal pressure p_i which is acting on the liner.

Figure 20 demonstrates the stiffening effect of the steel reinforcement at the inside of the centric penetration. We note here that the FLAXC 3 elements provide only membrane action for the liner component and reinforcement.

The results of computations with different prescribed displacements are shown in Fig. 21. We recognize that axisymmetric and three-dimensional solutions without the perforation cap zone yield almost identical solutions for a centric penetration. On the other hand, if perforations are accounted for in the global analysis we obtain a strong reduction of radial and axial stresses while the hoop stresses increase considerably. In other words, the standpipe penetration zone increases the radial expansion but decreases the displacement gradients.

The results of the eccentric penetration study indicates that the variation in the hoop direction remains negligible. Hence it suffices in the solution of a highly eccentric penetration using three-dimensional analysis to show results only at $\theta = 270^\circ$, see Fig. 22. Again we observe that the perforation cap has considerable influence on the results. The effects of idealisation are also demonstrated on this figure which displays results obtained from the global three-dimensional analysis of the 30° sector, in which the individual penetrations are idealised as shown in Fig. 14.

From a comparison of Figs. 21 and 22 we conclude that the eccentricity of the control rod penetrations has little influence, at least in the present case of the THTR 1:5 scale model. Hence, an axisymmetric idealisation seems to suffice for the detailed investigation. The main point at issue is then the computation of prescribed displacements which are used as input for this type of study. If we require an accurate insight into the behaviour of the immediate surrounding of a penetration, an elaborate three-dimensional analysis is needed taking into account the perforated cap zone. On the other hand, if we use prescribed displacements from an axisymmetric investigation neglecting the individual penetrations we obtain exaggerated radial and axial stresses, while the estimation of the hoop stresses appears to be much too low.

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HEXEC 27

FLAC 3

PENTAC 18

QUAMC 9

LINK

TRIMC 6

Fig. 1 SBB-Elements for Threedimensional Analysis

FLAXC 3

TRIAXC 6

RINGX

LINKX

QUAXC 9

Fig. 2 SBB-Elements for Axisymmetric Analysis

Fig. 3 Cantilever under Endshear
Data and Theoretical Tipdeflection

Fig. 4 Cantilever under Endshear
Accuracy of Tipdeflection

Triangular Element

Quadrilateral Element

Fig. 5 Multilinear Interpolation
From Nodes into Regions ① to ④

Triangular Element
7-Point Integration

Quadrilateral Element
3x3 Point Integration

Points of Numerical Integration Scheme

Fig. 6 Multilinear Extrapolation
From Regions ① to ④ toward Nodes

Fig. 7 Square Sheet
Input Data

Fig. 8 Finite Element Idealisation
Internal Energy Results

Fig. 9 Maximum Principal Stresses
Idealisation with TRIMC6

Fig. 10 Maximum Principal Stresses
Idealisation with QUAMC9

Fig. 12 THTR 1:5 Scale Model
Section A - B

Fig. 11 Prestressed Concrete Reactor Vessel
THTR 1:5 Scale Model

Fig. 13 THTR 1:5 Scale Model Axisymmetric Idealisation

Fig. 14 30° Sector of THTR 1:5 Scale Model Threedimensional Idealisation

$$\rho_j = 30 \text{ kp/cm}^2$$
$$\sigma_{rr} \left[\text{kp/cm}^2 \right]$$

$$\rho_j = 30 \text{ kp/cm}^2$$
$$\sigma_{zz} \left[\text{kp/cm}^2 \right]$$

Fig. 15 THTR 1:5 Scale Model
Contourlines of Radial Stress

Fig. 16 THTR 1:5 Scale Model
Contourlines of Axial Stress

Fig. 18 30° Sector of Perforated Cap
Threedimensional Idealisation

Fig. 17 THTR 1:5 Scale Model
Contourlines of Hoop Stress

Fig. 19 Controlrod - Penetration
Idealisation

Fig. 20 Centric Controlrod - Penetration
Asymmetric Analysis

Fig. 21 Centric Controlled - Penetration
Axisymmetric Analysis

Fig. 22 Eccentric Controlled - Penetration
Three-dimensional Analysis