

NONLINEAR ANALYSIS OF PRESTRESSED CONCRETE REACTOR PRESSURE VESSELS

S. BERG, S. LØSETH

*Division of Structural Engineering, SINTEF,
N-7034 Trondheim-NTH, Norway*

I. HOLAND

*Division of Structural Mechanics,
The Norwegian Institute of Technology, N-7034 Trondheim-NTH, Norway*

SUMMARY

A computational model for circular symmetric reinforced concrete shell problems is described. The model is based on the Finite Element Method. Non-linear stress-strain constitutive relations are used for the concrete, the reinforcement and for the liner. The reinforcement layers may be of different steel qualities. Each layer may be given a specified prestressing. This can be done at the beginning of the computations or the specific reinforcement layer can be considered inactive until a specified level of loading is reached. Thus, the prestressing procedure may also be analyzed in detail. Bond-slip effects are not accounted for. However, no bond may be assumed for prestressing cables by inserting special reinforcement elements.

Cracking of concrete is accounted for according to a principal strain criterion. Further, creep is analyzed using the "rate of creep" or the "linear superposition" method. Thus, the model is capable of covering the whole range of loading and the load history.

"Three-dimensional" axisymmetric elements are used for very thick shells. For more slender structures, thin shell elements are available. A combination is also possible. The three-dimensional elements may be used in regions where shear effects are important, and the thin shell elements in the other parts of the structure.

The equilibrium and the incremental equations are established by a summation of the contributions from the liner, the concrete and each reinforcement layer. These contributions are achieved by using a numerical integration scheme. The structure may in the analysis be subjected to several independent load vectors. The solution is performed in several load steps with equilibrium iterations for each step.

Several models of prestressed concrete reactor pressure vessels which have been tested up to rupture have been analysed, among them the models presented in SMIRT-2 Paper H 2/4 and SMIRT-3 Paper H 4/7. Some of these analyses are presented and the results are discussed giving special attention to the main factors influencing the behaviour. Analytical (numerical) models for reinforced concrete are also discussed on a more general basis.

1. Introduction

The axisymmetrical shell problem may be regarded as an extension or a generalization of a corresponding beam or frame problem. The model described here, is based on a frame model developed by Aldstedt [1].

The shell is modelled by a number of conical elements which may have a linear thickness variation, see Figure 1. In order to analyze shear and thick shell effects, solid elements are also available, see Figure 2. Work is going on in order to make a coupling of the two elements possible. Thus a very versatile model for analyzing axisymmetrical problems will be obtained.

2. Numerical model

2.1 Finite elements

The shell element has three degrees of freedom at each end node and one additional inplane d.o.f at the midpoint, see Figure 1. A more complete description is given in [2]. The element may include reinforcement both in the hoop direction and parallel to the generatrix. The program may handle eight layers totally. Complete compatibility in the deformation of concrete and reinforcement is assumed. Bond slip can also be taken into account by inserting separate elements for the reinforcement and for the bond characteristics. In these additional elements, zero concrete thickness is specified.

The element characteristics are obtained by using a combination of numerical and analytical integration. Through the shell thickness, the compression zone is integrated numerically with an optional number of Gaussian points, while the tensile zone is integrated analytically. The location of the Gaussian points will thus change during the computations. Numerical integration with an optional number of integration points are also used along the generatrix.

The solid element is a ring with a general quadrilateral cross section, see Figure 2. There are two degrees of freedom at each of the corner nodes. In order to improve the bending characteristics of the element, four nodeless degrees of freedom are included. The displacement associated with these nodeless variables may produce a parabolic incompatibility along the edges. This may be more questionable in nonlinear than in linear analysis. However, the experience so far is quite satisfactory.

The solid element may include hoop reinforcement and reinforcement orthogonal to the ring direction oriented arbitrarily in the plane of the cross section. A total number of eight layers can be included. Also here compatibility in deformation between reinforcement and concrete is assumed.

The element characteristics are obtained by using numerical integration. The number of the integration points is optional from one to four by four.

2.2 Stress-strain Relations

Several types of reinforcement may be used in the same structure. The stress-strain curve for each steel quality is given numerically. Each reinforcement layer can be given an initial strain. Furthermore, each layer can be considered as nonexisting up to a specified load level. Thus, the prestressing procedure can be analyzed in detail.

The stress-strain relations for the concrete are based on uniaxial stress-strain curves represented numerically. In the shell element the two directions are considered as uncoupled. The stress and the tangent modulus corresponding to the strain in the same direction, is computed from the uniaxial curve. Cracks are introduced when the strain have exceeded a specified tension limit. In a possible future modification, coupling of the two directions will be considered. A numerical representation of biaxial stress-strain relations as described in [3] (see also [4]), may be adopted. Path dependency should also be considered.

For the solid element, a crack criterion as shown in Figure 3 is adopted. Apart from this, the same procedure as described above is used for computing stress and tangent modulus in each principal direction. In a possible future modification, a more advanced stress-strain relationship will be considered for the solid element.

Creep in concrete is incorporated according to the rate of creep method and the linear superposition method. As very little data exist concerning bi- and three-axial creep laws, the directions are simply considered uncoupled also in this context.

2.3 Numerical Solution Procedure

The structure may be subjected to several independent load vectors, which are applied in increments. Within each increment, equilibrium is found by iterations. The tangent stiffness matrix is updated for each increment. During the equilibrium iteration, it may be kept constant or it may be recomputed for each cycle. The creep analysis is also performed stepwise within each load level according to specifications given by the user.

4. Numerical Example

Figure 4 shows a prestressed concrete pressure vessel with liner tested by FCB* [5]. The vessel is analysed with two different meshes of solid ele-

* Cement and Concrete Research Institute, The Norwegian Institute of Technology - University of Trondheim, Norway.

ments, see Fig.5. There are 20 prestressed bars in the axial direction with a total nominal prestressing force of 660 Mp. Hoop prestress cables are placed in grooves. The total nominal prestressing force is 66 Mp per ring in the mid region, and 78 Mp in the two rings at each end. In the coarse mesh the hoop cables are distributed over the whole surface while the real distribution is used for the fine mesh. The liner is modelled as reinforcement layers in two directions. This corresponds to the Tresca yield criterion when the stresses in the two directions are both compressive or tensile. When there is tension in one direction and compression in the other, the yield limit is overestimated.

The vessel is subjected to internal hydrostatic pressure represented by lumped forces at the nodal points. The two analyses were done with load increments corresponding to the load levels [0, 100, 150, 175, 200, 225, 250, 260, 270, 280] kp/cm² and [0, 150, 175, 187,5, 200, 215, 230, 240, 250, 260, 270, 280] kp/cm², respectively. The ultimate load of the test vessel was reached with leakage of water at a pressure of 288 kp/cm². In the analyses the ultimate load was found to be between 270 and 280 kp/cm². The end regions were found to be critical. A very pronounced compression dome effect was found. The crack pattern shown in Fig.6 indicates the shape of this dome effect. Radial cracking is shown in Fig.7.

Very good agreement with the test results was obtained concerning deformation, see Figures 8, 9 and 10.

The same vessel has been analysed with shell elements, see Fig. 11. Also for this analysis the computed displacements agree fairly well to the test curve, see Figures 12 and 13. The vessel has been analysed with both complete compatibility in deformations in the axial prestressing cables and the concrete and with free movement. Only insignificant differences in the results were observed. Results for the vessel M1 described in [5] and [6] are shown in Fig.14.

4. Discussion

Unusually, linear analyses are used when designing reinforced concrete structures. These analyses may simulate the behaviour very poorly for the whole load range. However, since an equilibrium model is used and there is usually ample deformation capacity in the structure, this design procedure functions satisfactorily.

There are advances in concrete material technology towards higher strength and more homogeneous quality in all respects. For these higher qualities, there will be less deviations from a linear stress-strain relationship for concrete in compression. Naturally, this development leads to relatively higher allowable stresses. At the same time the deformation capacity of the structure and hence the ability to redistribute the internal

forces, will be somewhat reduced. There will still be nonlinearity in the structural behaviour because of cracking of the concrete and plastic deformation of the reinforcement.

The factors mentioned above may lead to a larger need for nonlinear analytical models which are able to simulate the deformation path. At the present stage, however, such models have been used in design only for more special cases.

Even if large efforts for development of such models have been done in recent years, this work is at an early stage. The problems are very complex. Many input parameters are therefore necessary, both concerning the structure, the modelling of it, and the computational procedure. A systematic parameter study for one such model with test comparisons is a formidable task.

In many practical situations the problems are a bit simplified in that the compression zone is fairly little stressed. The deformation of the structure is thus to a large extent determined by cracking of the concrete and tensile strains in the reinforcement. In those cases, fairly accurate results are expected.

At the present stage, such nonlinear models can not be considered to be a tool for every structural engineer. Good knowledge of the model and numerical experience is very beneficial both for giving suitable input data and for judging the results.

5. Conclusion

The experience with the model so far is very satisfactory. However, modifications are considered beneficial. General bi- and three-axial stress-strain laws for concrete, including path dependancy, should be considered. At the present stage, however, a general stress-strain formulation must be based upon a very limited amount of test data. Therefore, a very simplified formulation should be preferred.

References

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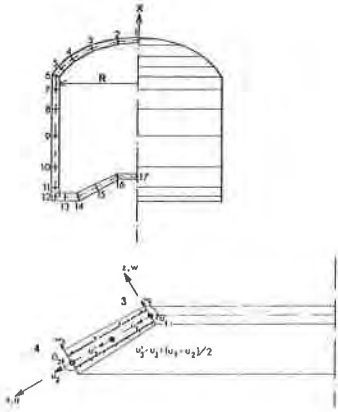


FIGURE 1 Shell Element

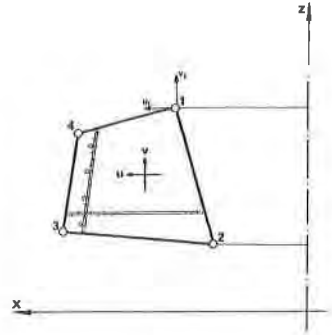


FIGURE 2 Solid Element

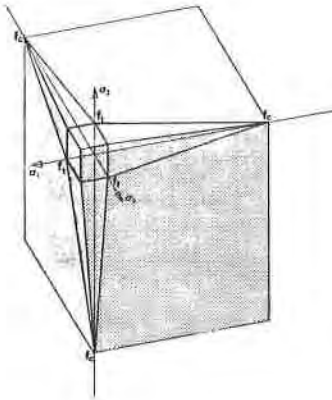


FIGURE 3 Crack Criterion for Solid Element

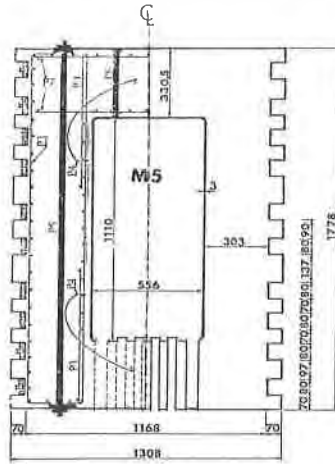


FIGURE 4 Model of a Prestressed Concrete Reactor Vessel

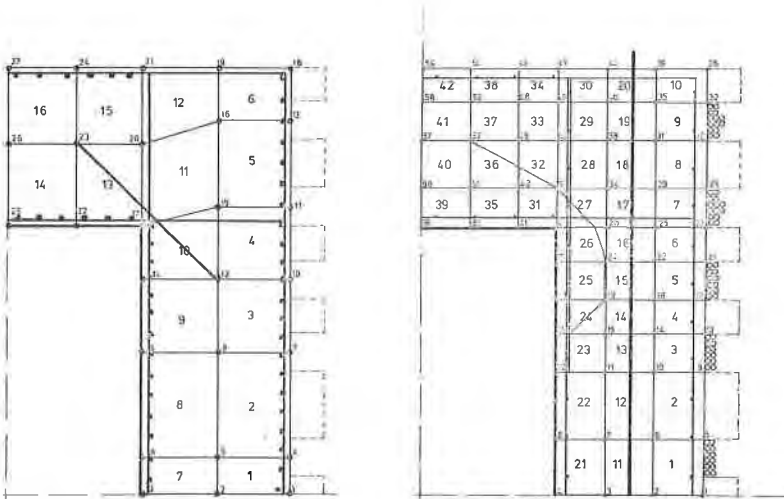


FIGURE 5 Finite Element Modelling - Solid Elements

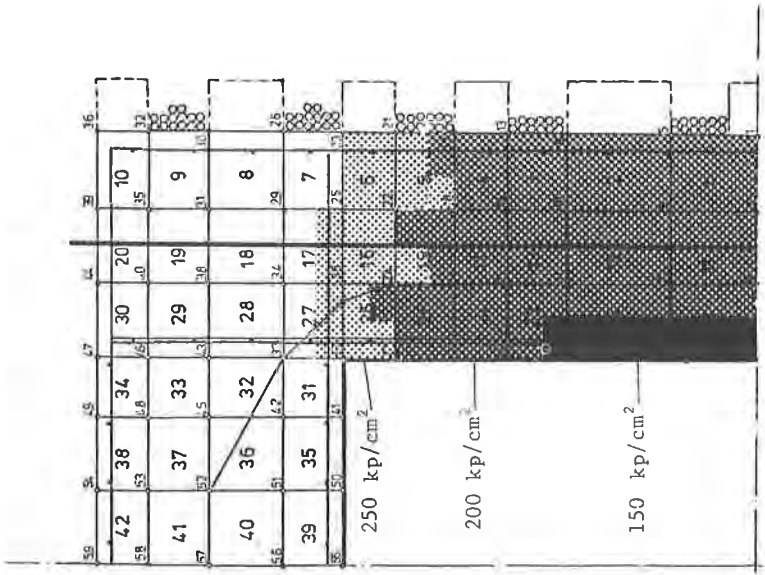


FIGURE 6 Crack Pattern at Load Level 250 kg/cm²

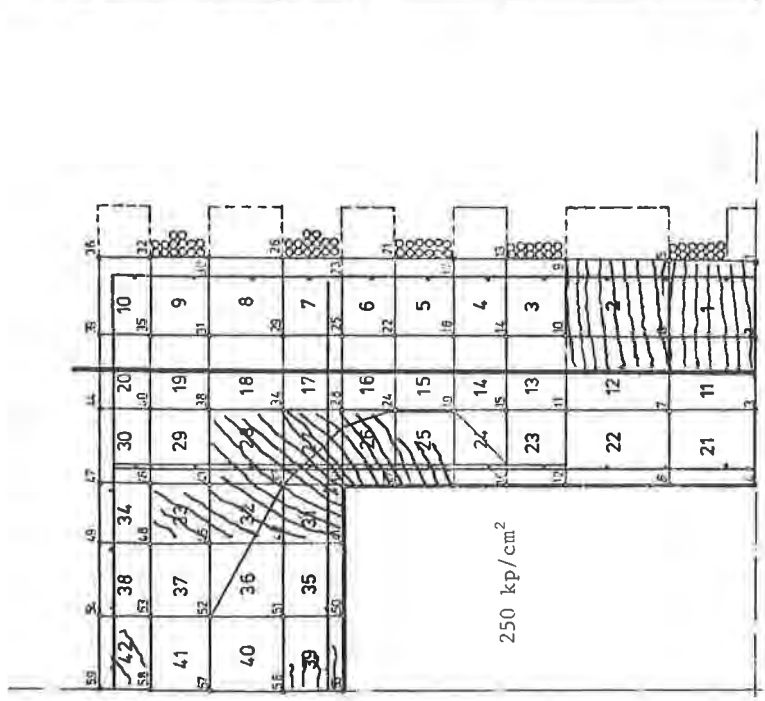


FIGURE 7 Radial Cracking at Different Load Levels

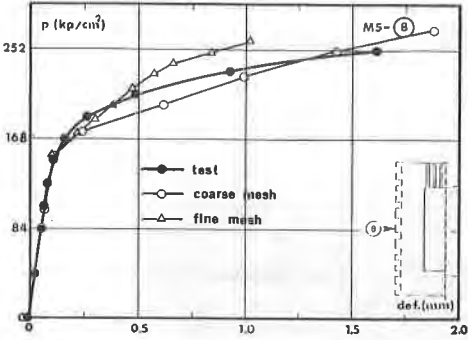


FIGURE 8 Radial Displacements - Solid Model

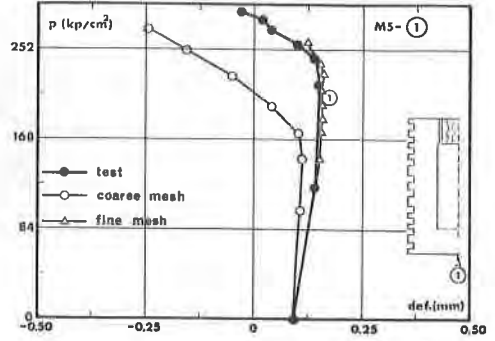


FIGURE 9 Axial Displacements - Solid Model

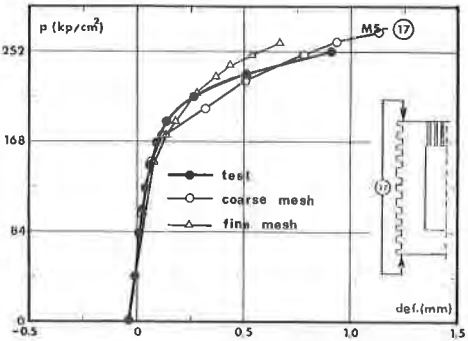


FIGURE 10 Axial Elongation - Solid model

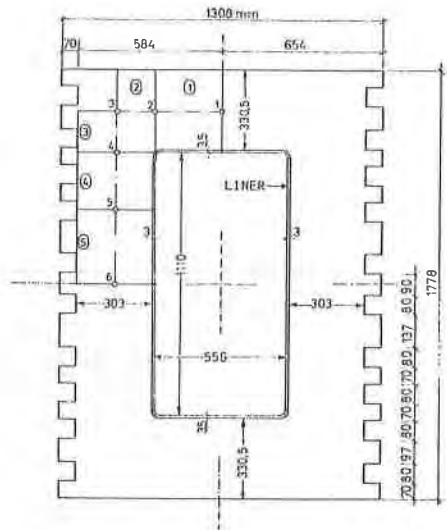


FIGURE 11 Finite Element Modelling - Shell Elements

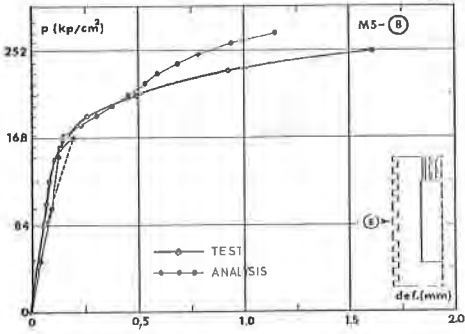


FIGURE 12 Radial Displacements - Shell Model

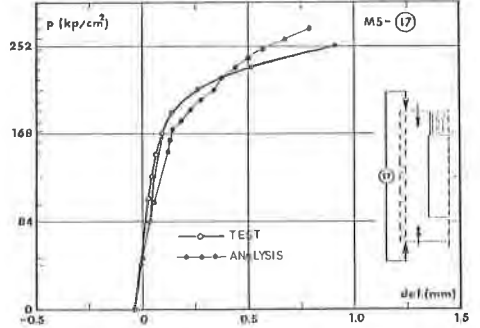


FIGURE 13 Axial Elongation - Shell Model

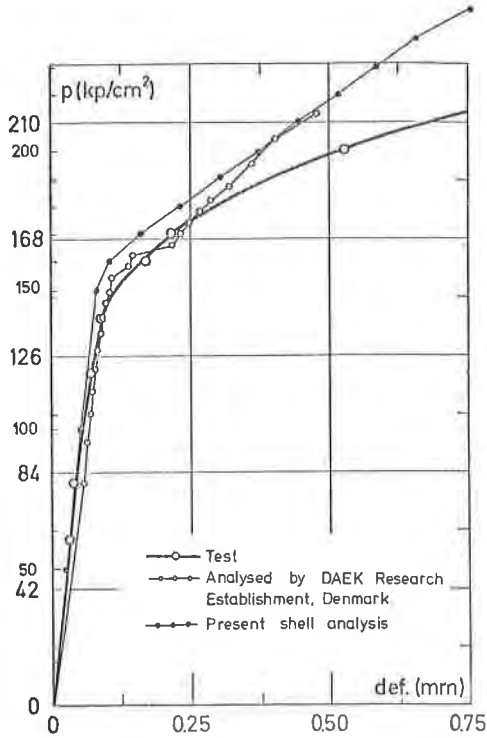


FIGURE 14 Radial Displacements - Shell Model M1