Cracking Analysis of a Prestressed Concrete Containment Structure

Analyse des fissures dans un réservoir en béton précontraint

Analyse der Rissbildung bei einem Spannbetonbehälter

Frano B. DAMJANIC
Prof. of Civil Eng.
Univ. of Ljubljana
Ljubljana, Yugoslavia

Joaquim A. FIGUEIRAS
Assoc. Prof.
Univ. of Porto
Porto, Portugal

Rui H.C.F. POVOAS
Assist. Prof.
Univ. of Porto
Porto, Portugal

Marjan STANEK
Senior Lecturer
Univ. of Ljubljana
Ljubljana, Yugoslavia

SUMMARY

A practical problem-related to the assessment of structural cracking is considered. The structure is analysed using two finite element models, i.e. two separate computer codes. Although the same numerical model for simulation of nonlinear concrete behaviour is employed, certain discrepancies in the numerical results are observed. This is mainly due to different modelling of boundary conditions and prestressing. Regardless of the problems mentioned, FEM is proving to be a most powerful engineering tool.

RÉSUMÉ

L'article traite de l'évaluation des fissures dans une construction. La construction a été analysée par deux modèles d'éléments finis. Bien qu'on applique le même modèle numérique pour la situation du comportement non-linéaire du béton, une divergence des résultats numériques a été observée. C'est dû surtout aux modèles différents des conditions limites et des forces de précontrainte. Cependant, la méthode est efficace pour l'analyse structurale.

ZUSAMMENFASSUNG

Der Beitrag behandelt die rechnerische Erfassung der Rissbildung eines Spannbetonbehälters. Bei der Analyse der Konstruktion wurden zwei entwickelte Modelle der Methode der finiten Elemente und das zugehörige Rechenprogramm verwendet. Obwohl das nichtlineare Verhalten des Betons in beiden Modellen gleich simuliert wurde, konnten Differenzen in den numerischen Ergebnissen festgestellt werden. Die Ursache liegt in den verschieden modellierten Randbedingungen und in der Vorspannung. Trotz dieser Probleme hat sich die Methode der finiten Elemente als ein sehr erfolgreiches Ingenieurmittel erwiesen.

1. INTRODUCTION

The 1st Conference on Computer-Aided Analysis and Design of Concrete Structures [1] held in Split in 1984 successfuly summarized a large number of numerical models and techniques, particularly these based on the finite element method, for the analysis of concrete structures. Since then, numerical modelling and solution techniques have been significantly improved. On the other hand, the advent of powerful computers, as well as microcomputers with parallel processing, endowed with the exciting prospect of developing an interactive design system gives the possibility that such techniques can be efficiently employed to the solution of complex practical problems. However, it is true to say that the numerical capability is nowadays in advance of the knowledge of concrete constitutive behaviour. The knovledge of concrete behaviour under triaxial stress states is incomplete; or at least no consistent constitutive relation has yet been established. Nevertheless, in spite of this fact, satisfactory results can be achieved in engineering practice. The 2nd ICC conference [2], together with another recent conference has proved this trend. However, having experience in both the fields, practical structural concrete design and finite element analysis, we are aware of all the problems, or quoting Ref. [3], "the current inconsinstencies" well summarized in Section 3 of the mentioned colloquium's introductory report. In this paper showing results of F.E. analysis of a practical problem we intend to point out certain issues primarely related to F.E.M. as an efficient designe-oriented analysis tool.

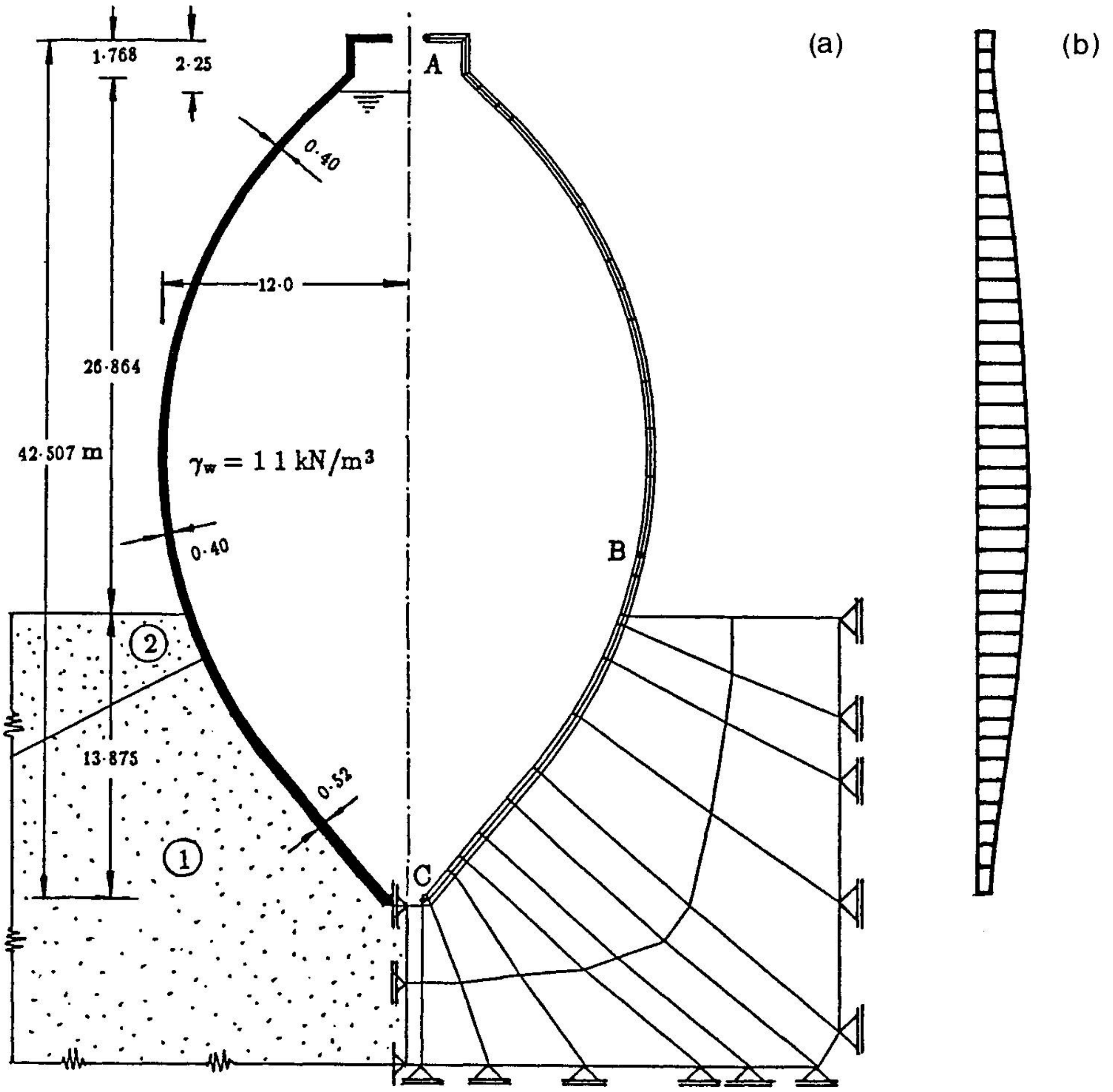

Fig.1 Prestressed concrete septic containment showing problem details and finite element idealisations: (a) axisymmetric mesh, and (b) shell element mesh.

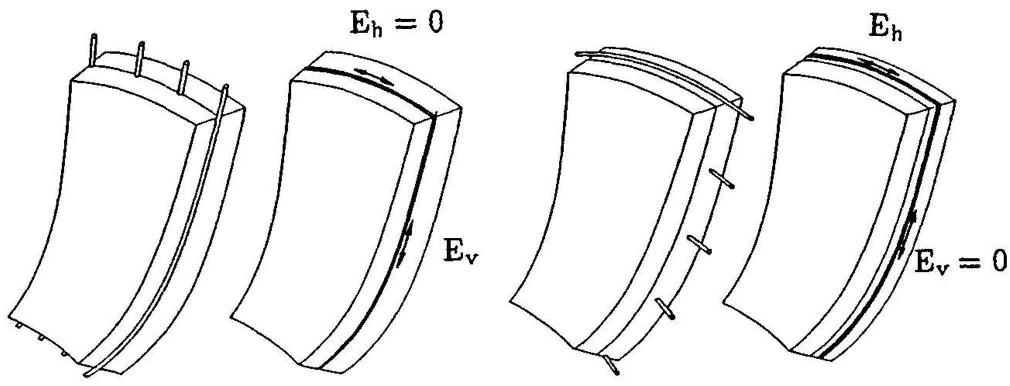

Fig.2 Prestressing cable position and finite element idealisation (Axi. elements).

The example here presented is related to the assessment of structural cracking of a prestressed septic containment under normal service loading. As a matter of fact, cracking of concrete structures very often occurs even far bellow service load conditions, and represents probably the main, and also undesirable, feature of concrete behaviour. Permiting insight into the cracking phenomenon (initiation, spreading and closing of cracks) the finite element method makes possible a rational analysis of concrete structures.

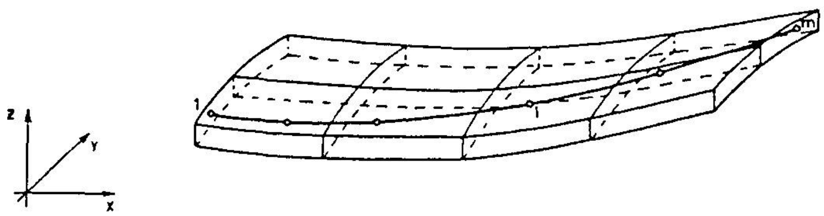

Fig.3 Geometry of the prestressing tendon (Shell elements).

The structure is analysed using our two finite element programmes (the first one based on the 2D/axisymmetric formulation [4] and the second based on the shell formulation [5]) for the non-linear analysis of reinforced and prestressed concrete structures. Numerical model employed in the programmes accounts for the most dominant nonlinear behaviour of concrete, e.g. multiaxial elastoplastic compressive behaviour including crushing, initiation and spreading of cracks etc. The prestressing cables are represented with discrete elements allowing uniaxial elastoplastic modelling of steel behaviour. The model is earlier developed [6-8] and further improved and extended. Results of several engineering studies [9-13] illustrate the applicability and practical merit of both the model and the codes.

2. ILLUSTRATIVE EXAMPLE

2.1 Problem description

The containment, a prestressed concrete structure shaped in an axial symmetric "amphora" form, was earlier designed for the sewage treatment plant of the city of Ljubljana. The design followed a "standard" engineering manner; a linear elastic finite element code was employed to determine internal forces, than reinforcement arrangement was defined. Essential details of the structure designed are given in Fig.1. Approximatively one third of the structure, the lower conical part, is "implanted" into the soil. No additional structural foundation elements are designed. The structure is reinforced with vertical (meridional) prestressing cables located in the middle of the structural wall cross section, and horizontal (circumferential) prestressing cables are close to the outer surface of the wall. There are 96 meridional cables all together. However, the lenght of 24 cables is practically from the top to the bottom of the structure. The rest of them are located in the mid-hight of the structure to reinforce the widest part of the structure. The total number of circumferential cables is 142. The effective prestress forces (after initial prestressing losses) of 600 kN/cable and 500 kN/cable are expected to act in meridional and cicrumferential cables respectively. One of the major requirements for the structure is that structural cracking is not permitted due to very agressive contents of the waste water. Since the structure was designed assuming prestressed concrete as a homogeneous isotropic linear elastic material we reanalysed the containment using two non-linear F.E. codes (Axisymmetric and shell formulation). Finite element mesh discretizing the structure and a part of surrounding soil for the axisymmetric analysis is shown in Fig.1(a). The prestressing cables are represented by a pair of membranes of equivalent thickness (Fig.2) and the influence of the prestress forces due to curved shape of the structure by external equivalent pressure (as suggested in Ref.(14). For the shell analysis a vertical section (6 degrees) of the structure is discretized with 44 shell elements shown in Fig.1(b). Prestressing cables are modelled as indicated in Fig.3 using a tendon formulation [12]. Soil influence is simulated by equivalent springs at the appropriate nodes.

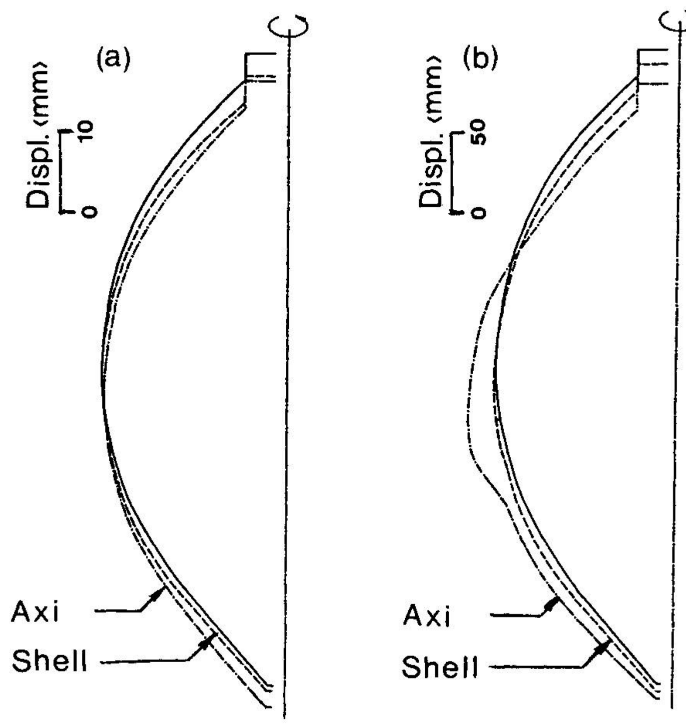

Fig.4 Deformed shapes due to: (a) Self-weight and prestressing, and (b) servis load.

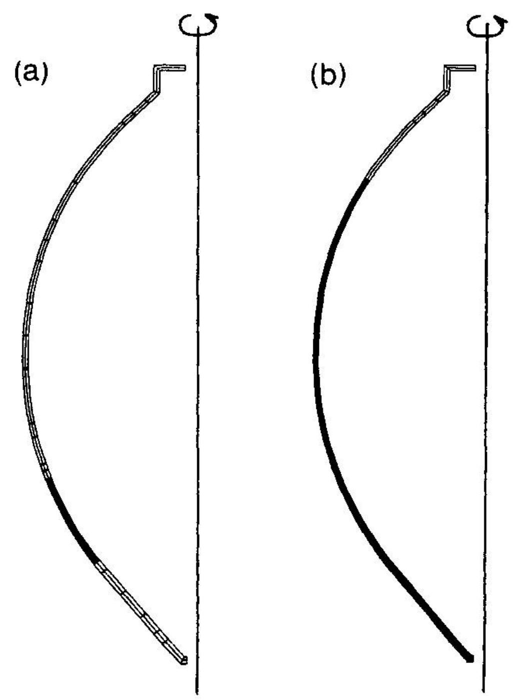

Fig.5 Tensile cracking zones using: (a) Shell formulation, (b) Axisymmetric formulation.

2.2 Numerical results

The structure is analysed under the conditions of prestress and internal hydrostatic pressure equivalent to the containment filled up to the maximum level (See Fig.1). The deformed structure profiles, i.e. the prestressed configuration and the configuration at the full service load compared to the initial configuration of the structure are illustrated in Fig.3. No cracks are predicted under the prestressing conditions. However, vertical cracks throughout the thickness of the structure are predicted at the service load conditions. The zones of vertical cracks are indicated in Fig 5. The max. crack width (supposing a crack distribution at the position of meridional cables only) is estimated in the range of 1.13 mm (axisymmetric analysis) and 0.5 mm (shell analysis). Displacements obtained using the two codes are compared in Table 1. Significant stresses in cables and in concrete are listed in Tables 2 and 3 respectively. Considering two set of the results it is clearly seen that: (a) vertical cracks will occur, and (b) the shell formulation predicts a rather stiffer structural response. The differences in the results are primarely due to different modelling of: (a) prestressing and (b) influence of the surrounding soil. More realistic prestress modelling is applied in the shell analysis (Equivalent load in the axisymmetric). On the other hand, soil interaction in the axisymmetric is modelled in a more appropriate way analysis.

Displacements [mm]		SHELL	AXISYMMETRIC
Load case 1: g + p	top	$u_r = 0.004$ $u_z = -3.08$	$u_r = \approx 0$ $u_z = -3.59$
	bottom	$u_r = -0.016$ $u_z = -0.837$	$u_r = -0.005$ $u_z = -3.03$
Load case 2: g + p + w	top	$u_r = 0.016$ $u_z = -9.88$	$u_r = \approx 0$ $u_z = -22.84$
	bottom	$u_r = -0.912$ $u_z = -5.17$	$u_r = 0.271$ $u_z = -8.86$

Table 1: Radial and vertical displacements.

Min&Max stresses in prestressing cables $*10^6$ [kN/m^2]		SHELL	AXISYMMETRIC
Load case 2: g + p + w	circum.	0.90 - 1.04	0.89 - 1.23
	meridional	1.07 - 1.08	1.07 - 1.50

Table 2: Extreme stresses in the cables.

Max. compressive stress in concrete [kN/m^2]		SHELL	AXISYMMETRIC
Load case 1: g + p	circum.	-8720	-735
	in plane	-3201	-1138
Load case 2: g + p + w	circum.	-3596	-486
	in plane	-2926	-3891

Table 3: Max. principle compressive stress.

3. DISCUSSION AND CONCLUSIONS

The brief description of the results obtained analysing one single structure using non-linear FE analysis and applying practicaly the same consitutive model for the simulation of R.C. behaviour, but based on two different formulation indicates the following:

* Non-linear FE analysis is (or if there is any doubt, it will be definitively very soon) one efficient reliable and practical design-oriented analysis tool which is perfectly consistent with "strut-and-tie model" (STM) concept.

* It seems that using FE structural analysis a step-by-step procedure (Firstly linear FE analysis, dimensioning, and than fully non-linear FE "control") has to be used.

* Although the same concrete constitutive model is employed in the two analyses presented the results are a rather different. This is not due to two different formulations applied, but primarely due to different boundary condition interpretations.

* In additon to the above, we can conclude that nowadays a large number of concrete constitutive models, from a very simple one (if we do not take into account the "historical" linear elastic) to very sophisticated are spreaded and applied in practice. In this case, applying different models included in a FEA, a spectrum of different results for the same example would be obtained. An immediate question is: What is

a real "truth"? Which model is the most reliable, appropriate, or correct? This is a natural question or dilemma of any researcher and designer. From the FEA aspects we may conclude, as we mentioned earlier, that the numerical capability is in advance of the konwledge of structural concrete behaviour.

Therefore we strongly support the initiative to consider the list of "challenges" (Section 5, Ref. [3]) in the colloquium. Furthermore, we expect from the colloquium to make a general, but an organized step forward in structural concrete design.

REFERENCES

1. Proc. 1st Int. Conf. Computer-Aided Analysis and Design of Concrete Structures, Eds. F.B.Damjanic et al., Pineridge Press, UK, 1984.
2. Proc. 2nd Int. Conf. Computer-Aided Analysis and Design of Concrete Structures, Eds. N.Bicanic, H.Mang, Pineridge Press, UK, 1990.
3. BREEN J.E., Why Structural Concrete. Preliminary invited lecture at IABSE Colloquium "Structural Concrete", Stuttgart, 1991.
4. DAMJANIC F., A Finite Element Technique for Analysis of Reinforced and Prestressed Concrete Structures. Finite Element Methods for Nonlinear Problems, Eds. P.Bergan, K.J.Bathe, W.Wunderlich, Springer, Berlin, 1986, p.623-637.
5. OWEN D.R.J., FIGUEIRAS J.A., Ultimate Load Analysis of Reinforced Concrete Plates and Shells Including Geometric Nonlinear Effects. Finite Element Software for Plates and Shells, Eds. E.Hinton, D.R.J.Owen, Pineridge Press, UK, 1984, p.235-326.
6. DAMJANIC F.B., Reinforced Concrete Failure Prediction under both Static and Transient Conditions, Ph.D. Thesis, University of Wales, 1983.
7. FIGUEIRAS J.A., Ultimate load analysis of anisotropic and reinforced concrete plates and shells. Ph. D.Thesis, University of Wales, 1983.
8. OWEN D.R.J., FIGUEIRAS J.A., DAMJANIC, F., Finite element analysis of reinforced and presstresed concrete structures including thermal loading. Comp. Meth. Appl. Mech. Engng., 41, 1983, p.323-366.
9. FIGUEIRAS J.A., OWEN D.R.J., Nonlinear Analysis of Reinforced Concrete Structures. Computer-Aided Analysis and Design of Concrete Structures, Eds. F.B.Damjanic et al., Pineridge Press, UK, 1984, p.509-532.
10. DAMJANIC F., Finite Element Analysis of Buried Reinforced Concrete Pipes under Internal Pressure. NUMETA/85, Eds. J.Middleton, G.Pande, Balkema, Rotterdam, Netherlands, Part 2, 1985, p.679-686.
11. FIGUEIRAS J.A., Design of RC Shells by Using a Finite Element Nonlinear Model. Numerical Methods for Non-linear Problems, Eds. C.Taylor et al., Pineridge Press, UK, Vol.3, 1986, p.1276-1286.
12. POVOAS R.H.C.F., FIGUEIRAS J.A., Nonlinear Analysis of Prestressed Concrete Shells: Tendon Formulation. Computational Plasticity: Models, Software and Applications, Eds. D.R.J. Owen et al, Pineridge Press, Swansea, 1989, p.1379-1394.
13. STANEK M., DAMJANIC F.B., CELCER V., Cracking Prediction of a Prestressed Concrete Septic Containment. Computer-Aided Analysis and Design of Concrete Structures, Eds. N.Bicanic, H.Mang, Pineridge Press, UK, 1990, p.623-631.
14. BRUGGELING A.S.G., An Engineeringg Model of Structural Concrete. Preliminary invited lecture at IABSE Colloquium "Structural Concrete", Stuttgart, 1991.