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BUCKLING AND FAILURE ANALYSIS OF COOLING TOWER AND ITS APPLICATION TO A REAL CASE

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ABSTRACT

The paper presents a computational model for reinforced concrete multilayered shell element taking into account geometrical and physical non-linearities. The shell element results from the superposition of a plate element based on the discretization of the Mindlin theory, and the CST element. The initial curvature is incorporated using the Marguerre shallow shell theory. The constitutive model for the uncracked concrete is based on the elastoplastic theory and for the cracked concrete a tension softening behaviour is assumed. The description of the motion is made in the corotational Lagrangian formulation. The numerical part of the paper contains a detailed study of a built cooling tower. It is shown that the buckling load resulting from linear prebuckling analysis is considerably larger than the ultimate load.

1 INTRODUCTION

Reinforced concrete shells are of special interest since they possess a high load bearing capacity while using an extremely low amount of material. Such optimized structures, however, often exhibit a strongly non-linear behaviour. Due to its clear mathematical describability, the questions of geometrically non-linear behaviour can be viewed as mostly answered. In the case of physically non-linear responses, however, there are still many open questions.

The aim of this work is to develop a finite element model for general layered shells with the assumption of non-linear material in combination with geometric non-linearity. This model is used to study a real cooling tower submitted to its dead weight and to the wind pressure. For this kind of structure, the demonstration of a sufficient degree of safety against buckling has been considered to be one of the most important factors. However, when dealing with reinforced concrete cooling towers subjected to wind loads, the situation is characterized by several zones of tensile forces. Consequently, fracture of concrete in tension rather than its failure in compression should be expected to initiate the process of the collapse.

This has motivated the writers to investigate whether or not buckling loads, based on a linear elastic material, are a relevant parameter for assessing the structural safety of reinforced concrete cooling towers.

In order to be able to answer this question, a concept for ultimate load analysis of shells was developed. This concept considers :

- non-linearity of concrete in the compression-compression and the compression-tension domains
- fracture of concrete within the framework of the smeared crack concept with the assumption of a tension-softening behaviour for the cracked concrete
- strain hardening of the reinforcement steel
- geometric non-linearity.

2 THEORETICAL CONCEPT

2.1 Finite Element model

The element used results from the superposition of the Constant Strain Triangle (CST) and the Discrete Shear Triangle (DST) proposed by Batoz (1989). The introduction of the Marguerre shallow shell theory to incorporate the effects of the initial curvature gives a curved shell element (DSTM). The effect of coupling membrane and bending creates the membrane locking phenomenon which is treated by the mode decomposition technique (Stolarski et al.,1983).The formulation of the DST element is based on a generalization of the discrete Kirchhoff technique to include the transverse shear effects. DST has a proper rank and is free to shear locking.The DSTM element now possesses five degrees of freedom at each node. The sixth degree associated with the shell normal rotation is the drilling rotation proposed by Bergan and used in Marguerre theory by Frey. Figure 1 shows the stages of the construction of the DSTM element.

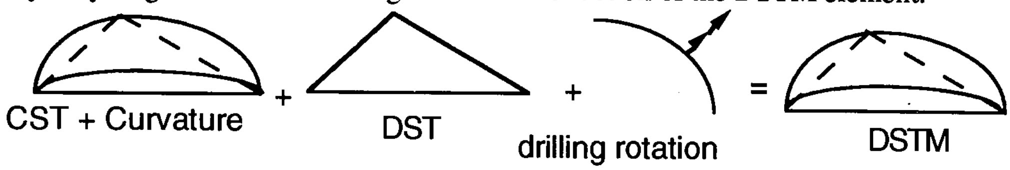


Figure 1 - Construction of the DSTM element

The two materials (concrete and steel) are individually represented : the concrete by the DSTM element and the steel by the CST element. A layered approach is realized by the computation of the integral expressions at GAUSS points according to the thickness of the element (Figure 2).

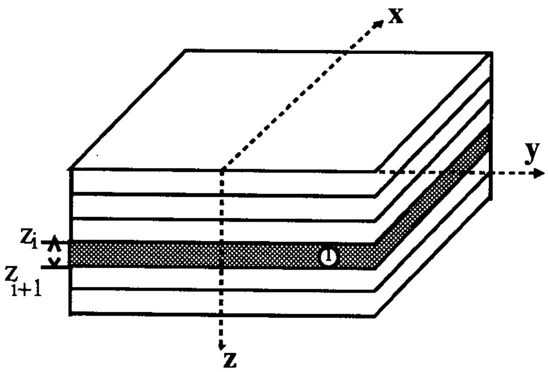


Figure 2 - Layered approach

2.2 Geometric relationships

Non-linear strain-displacement equations restricted to the consideration of large rotations and small strains are applied within the framework of a corotational Lagrangian description.On the basis of Mindlin's normal hypothesis, the strains are obtained as :

$$e_{ij} = e^{(0)}_{ij} - z\,\chi_{ij}$$

where $e^{(0)}_{ij}$ are the middle surface strains and χ_{ij} are the curvature of the middle surface. It is assumed that Mindlin's normal hypothesis is an acceptable approximation also for the crackedsubregions of the shell.The middle surface strains can be written as :

$$e^{(0)}_{ij} = \varepsilon_{ij} + \eta_{ij}$$

where ε_{ij} is the linear and η_{ij} is the non-linear part of the strain tensor ε_{ij} can be decomposed as :

$$\varepsilon_{ij} = \varepsilon'_{ij} + \varepsilon^{*}_{ij}$$

ε^*_{ij} is the effect of the initial curvature in Marguerre theory.

Details concerning ε^*_{ij}, ε'_{ij} and η_{ij} are given elsewhere (Chahrour, 1991).

2.3 Material modeling

Each layer of the shell is assumed to be in state of plane stress. We have used a strain hardening plasticity approach, with associated flow and isotropic hardening, to model the compressive behaviour of the concrete (Nadai yield criterion), and a smeared fixed crack approach for modeling cracking (Merabet 1990, Djerroud 1992). A crack is assumed to occur in the plane perpendicular to the maximum principal tensile stress when a stress based failure surface is attained. After cracking, concrete is assumed as orthotropic material with certain stiffness normal to and parallel to the crack plane with no coupling between the normal strain and the shear strain. Indeed, due to bond effects, cracked concrete carries a certain amount of tensile force normal to the cracked plane.

Concerning the reinforcing bars, a classical elasto-plastic strain hardening model is used with bilinear or trilinear diagram. Full bond is assumed at the concrete/reinforcement interface, i.e. the strain of a steel layer can be directly obtained form the strain tensors of the middle surface.

2.4 Linear stability criterion

The stability of a structure is investigated using the method of adjacent equilibrium which is also called Euler's method. If λ is the critical load level leading to instability and if the initial displacements can be considered as very small, the stability criterion is :

$$\det (K_0 + \lambda K_\sigma) = 0$$

K_0 is the infinitesimal matrix and K_σ is the initial stress matrix.

3 ANALYSIS OF COOLING TOWER SHELL

This example concerns a project of cooling tower to be erected in France.The aim of this simulation is to describe the behaviour of the structure under its dead load and increasing wind load, from the uncracked state until final collapse, and to compare the linear buckling load with the ultimate load.

3.1 Shell geometry and loading

The geometry and the finite element discretization are given in Fig. 3. Because of the symmetry of the wind load, only the half of the structure is analysed with the assumption of fixed base and elastic supports. The geometrical non-linearity and the interaction between the soil and the structure are neglected. The shell section is subdivided into ten concrete layers and the grid is made of two orthogonal bar layers. The wind pressure is given by the French Code C.R.T.(1991). Table 1 shows the results of the linear prebuckling analysis carried out with three combinations of the dead weight (G) and the wind load (W+S).

3.2 Numerical results

As shown in figure 4, the load-displacement path consists of two main parts, characterized by intact and fractured concrete. The second part can be divided into two sections: a hardening section of the partially fractured structure, and the yield plateau wich leads to the collapse. The critical load intensity corresponding to linear buckling is 14.4 x wind load (Table1: G+λ(W+S)). It is considerably larger than the ultimate load. This shows that a buckling analysis with linear elastic material is not sufficient to estimate the failure load of the shell.

This simulation is achieved considering only material non-linearity. It was demonstrated that disregard of the geometrical non-linearity for similar types of shells gives a stiffer response for the hardening section (Chahrour et al., 1992) with a difference of 15%. However the geometrical non-linearity can bring a stiffer solution in the special case of the parabolic cylinder tested by Mang et al. (1983).The deformed shape of the shell, the crack patterns for the two extreme layers (n°1 & n°10) and the distribution of the strains in the meridian reinforcing bars are given Fig.5-6.

4 CONCLUSION

For the cooling tower analyzed, linear buckling load is considerably larger than the ultimate load. Because this cooling tower may be regarded as a typical representation of the given class of shells, it seems reasonable to extrapolate from the results obtained that the failure of wind-loaded cooling towers made of reinforced concrete is initiated by rapid propagation of cracks in the tensile zones and not by buckling. Consequently, analysis concepts which are based on buckling are inadequate for even an approximate assesment of failure loads of reinforced concrete cooling tower shells.

The shell element that we have developed is robust,efficient and simple. Its formulation includes the shear effects and it leads to good performance for thin and thick shells without locking phenomena. Nevertheless the computing time on element level is relatively large because the numerical integration is also performed in the shell's thickness direction.

REFERENCES

BATOZ J.L., LARDEUR P,1989
"A discrete shear triangular nine dof element for the analysis of thick to very thin plates", IJNME, Vol. 28, pp 533-560

STOLARSKI H., BELYTSHKO T., CARPENTER N., 1983
"Bending and shear mode decomposition in C° structural elements", J. Struct. Mech. Div. Vol. 11 , n° 2, pp 153-176

MERABET O., 1990
"Modélisation des structures planes en béton armé sous chargements monotone et cyclique. Construction et validation d'un modèle numérique",Doctoral dissertation, INSA Lyon, France.

DJERROUD M., 1992
"Contribution à l'analyse des pièces fléchies en béton armé sous chargements monotone et cyclique ", Doctoral dissertation, INSA Lyon, France.

CHAHROUR I., 1991
"Contribution à l'analyse non linéaire matérielle et géométrique des coques en béton armé", Doctoral dissertation, INSA Lyon, France.

C.R.T, 1991
Cahier des Règles Techniques-Ouvrages en béton des réfrigérants atmosphériques, EDF,France

CHAHROUR I., MERABET O., DJERROUD M., REYNOUARD J.M., 1992
"A contribution to the physically and geometrically nonlinear analysis of reinforced concrete shells".International Conference on Fracture and Damage of Concrete and Rock (FDCR-2), Proceedings, Vienna, Austria, 9-13 nov

MANG H.A.,FLOEGL H.,TRAPPEL F.,WALTER H., 1983
"Wind-loaded reinforced concrete cooling towers: buckling or ultimate load ?" Journal of Structural Engineering, Vol 5, pp 163-170

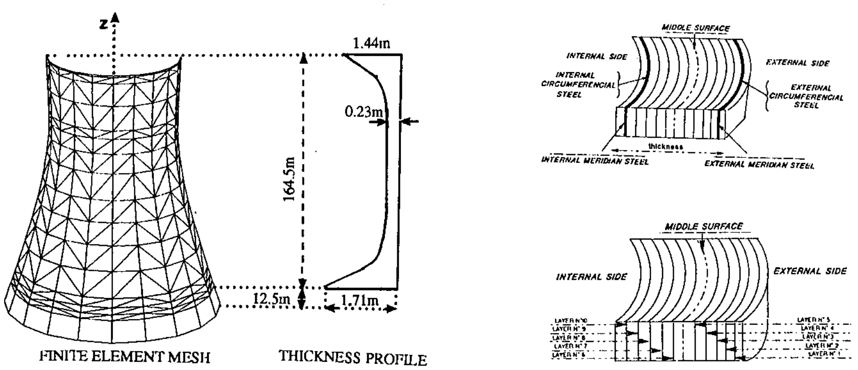


Figure 3 - Dimensions of the shell and FE mesh

Table 1: Critical buckling loads

Loading	$\lambda_{critical}$	Mode
λ(G+W+S)	12.805	4
G+λ(W+S)	42.688	4
λG	14.194	6

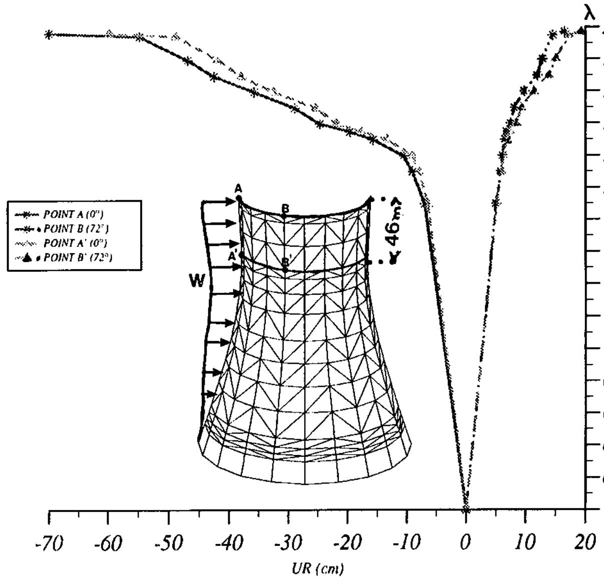


Figure 4 - Load-displacement curves

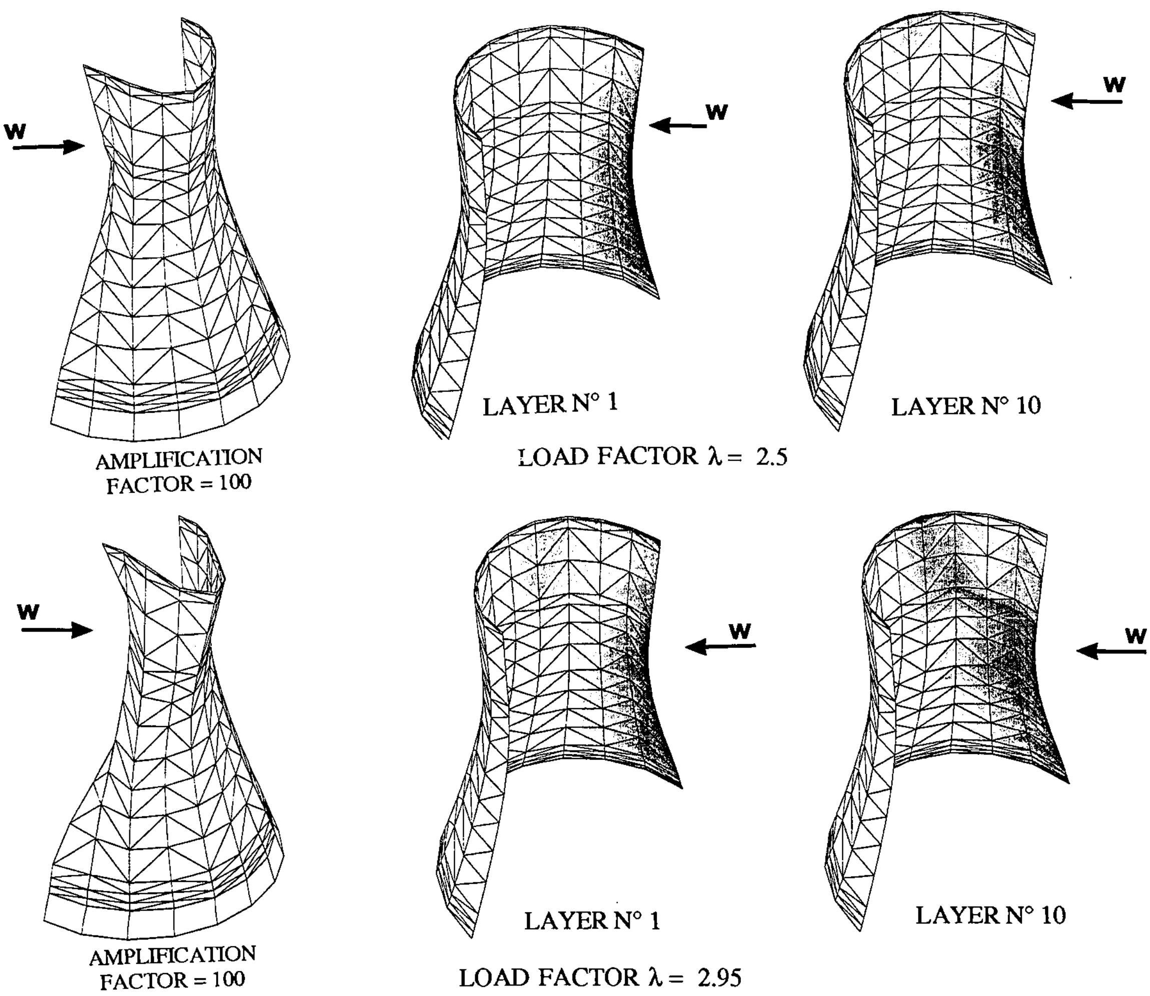
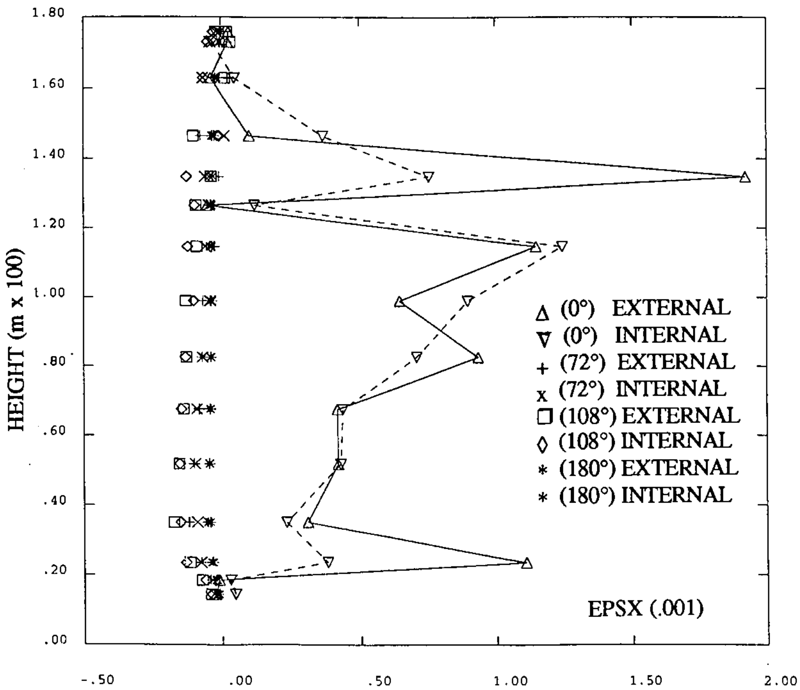
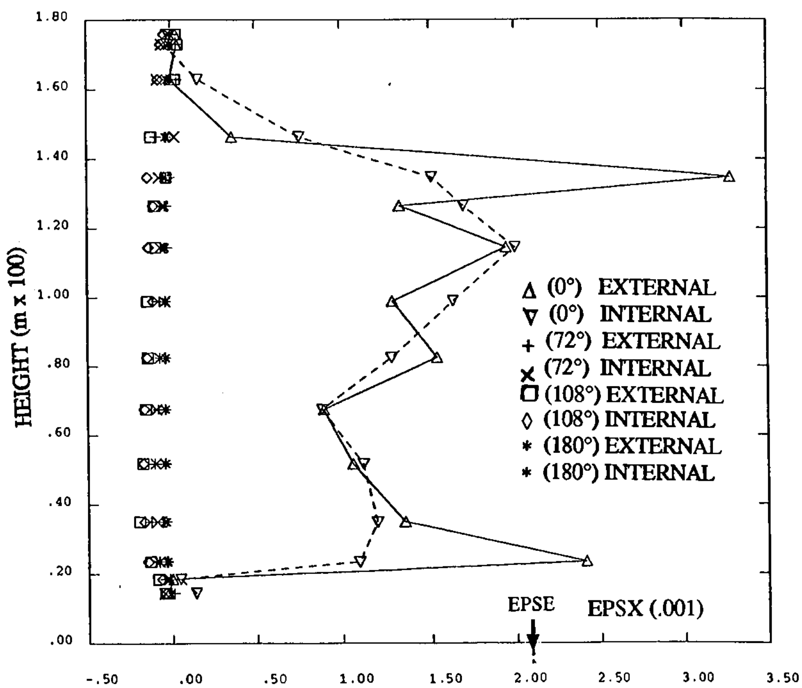


Figure 5 - Deformed shape of the shell and crack patterns



DEFORMATION OF MERIDIAN STEEL
at λ = 2.5



DEFORMATION OF MERIDIAN STEEL
at λ = 2.95

Figure 6 - Distribution of strains in the meridian reinforcing bars