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Autor: Meschke, G. / Mang, H.A.
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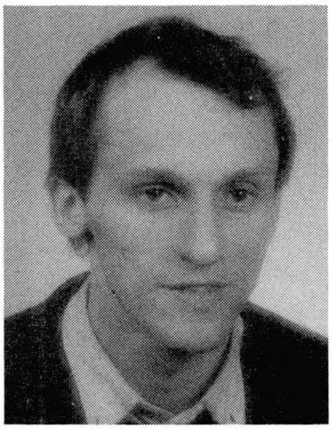
Evaluation of the Safety of a Cracked Concrete Cooling Tower

Estimation de la sécurité d'une tour de refroidissement dont le béton est fissuré

Untersuchung der Sicherheit eines gerissenen Stahlbetonkühlturmes

G. MESCHKE
Univ. Assist.
Technical Univ. Vienna
Vienna, Austria



Günther Meschke, born 1958, graduated as Dipl. Ing. in 1983 and as Dr. techn. in 1989, both from TU Vienna. Since 1983 he has been involved in research projects in the field of computational mechanics of concrete.

H. A. MANG
Professor
Technical Univ. Vienna
Vienna, Austria

Herbert A. Mang, born 1942, graduated as Dr. techn. (1970) from TU Vienna, Ph. D. (1974) from Texas Techn. Univ.; University Assistant (1967), Professor (1983), both at TU Vienna; Corresp. Member of the Austrian Academy of Sciences.

SUMMARY

The limit of serviceability and the residual safety against structural collapse of a cracked concrete cooling tower, which was built 25 years ago, is evaluated numerically by the finite element method. The process of damage is simulated by means of different thermal load histories. Several assumptions concerning the degree of corrosion are made.

RÉSUMÉ

La méthode des éléments finis a permis d'estimer numériquement la limite de service et la réserve de sécurité vis-à-vis d'une ruine de la structure, dans le cas d'une tour de refroidissement construire il y a 25 ans, dont le béton est fissuré. Le processus de détérioration est simulé à partir de considérations concernant différentes applications de charges de type thermique, ainsi que selon différentes hypothèses sur l'état de corrosion des armatures.

ZUSAMMENFASSUNG

Mit Hilfe der Methode der Finiten Elemente wird die Gebrauchssicherheit sowie die Traglast eines 25 Jahre alten, durch Risse beschädigten Kühlturms bestimmt. Der Schädigungsprozess – Ausbildung vertikaler Risse infolge von Temperaturspannungen – wird mit verschiedenen Annahmen für die Abfolge der Temperaturbeanspruchung sowie für die Entwicklung der Korrosion des Betonstahles nachvollzogen.

1. PRELIMINARY REMARKS

Concrete structures which were designed and built in the 1950's and 1960's frequently show signs of damage such as cracks, caused, e.g., by thermally induced stresses, which usually were not considered adequately by the design provisons of that time [1]. This paper demonstrates the role of nonlinear finite element analyses in the context of the evaluation of the residual safety coefficient of a cracked natural draught concrete cooling tower, which was built 25 years ago. With regards to "safety", loss of serviceability is considered as well as the limit state, characterized by the ultimate load.

The cooling tower Ptolemaïs-III is part of a 125 MW power station located in Ptolemaïs, Greece. The present state of the cooling tower shell is characterized by an approximately uniform distribution of long meridional cracks of crack width up to ~ 1 cm, which are distributed more or less evenly along the cirumference (Fig.1a).

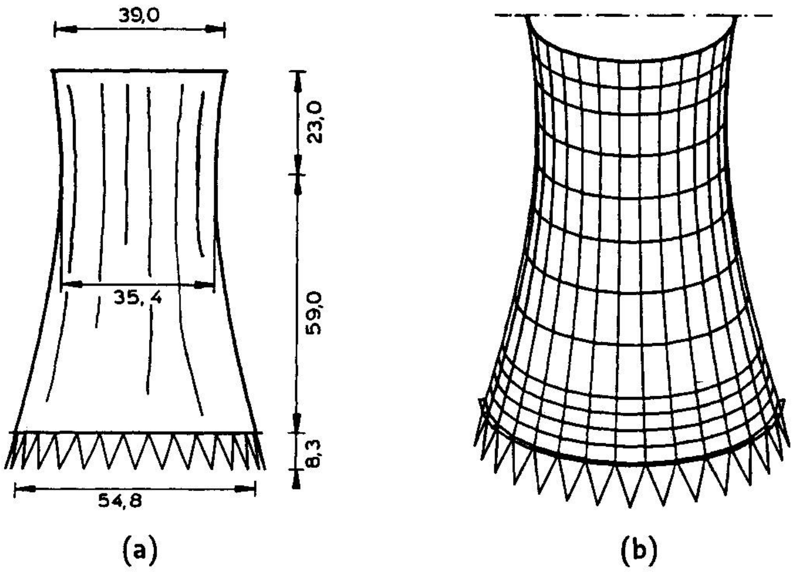


Figure 1: Meridional cracks, geometry, and finite element discretization of the Ptolemaïs cooling tower; (a) meridional cracks and geometry; (b) finite element discretization

The shell is supported by 30 pairs of concrete columns. Except for a small zone of ~ 9.3 m heigth at the lower part of the shell, the structure is reinforced by only one layer of reinforcement located in the middle of the shell. The thickness of the shell is 10 cm with the exception of the aforementioned lower part of the shell, where the thickness is gradually increasing from 10 cm to 50 cm towards the base.

Following a detailed in-situ inspection it was concluded (having rejected improbable causes of the damage) that the temperature gradient between the inside and the outside surface of the cooling tower shell according to winter conditions is the most likely cause for the development of the observed meridional cracks.

2. OUTLINE OF THE NUMERICAL PROCEDURE

2.1 Finite Element Model

The numerical investigation is based on an incremental – iterative procedure with the step size being adapted to the degree of nonlinearity of the structural behaviour. Fig.1b shows the chosen finite element mesh. Because of symmetry of the wind loading, only one half of the shell needs to be considered for the analysis. The shell and the stiffening rings located at the crown and at the bottom of the shell, respectively, are discretized by 225 quadrilateral shell elements [6]. Each element is subdivided into 13 layers such that approximately a plane state of stress may be assumed in each layer. As has been verified by a mesh sensitivity study based on a consistent refinement of the mesh [2], the selected discretization is sufficiently fine. The supporting columns are treated as beam elements (Fig. 1b) with axial as well as bending stiffness.

2.2 Constitutive Model

The numerical representation of cracked concrete is based on the "smeared-crack" approach. Cracks will open normal to the direction of the maximum principal stress when this stress exceeds the tensile strength f_{tu}. After crack initiation, tensile stresses are gradually released according to a linear post-peak stress-strain-relationship defined by a constant softening modulus E_S [2], [4]. The residual interface shear transfer across cracks, resulting from the roughness of the crack face and the dowel action of the reinforcing bars, is considered by means of a crack-strain dependent shear modulus G_c [2]. Tension stiffening is disregarded.

A linearly elastic - ideally plastic constitutive law is assumed for the reinforcement steel. The meridional and the circumferential reinforcement bars are smeared to mechanically equivalent, thin layers of steel which only have axial stiffness in the respective direction (orthotropic material). Corrosion is considered by multiplying the diameter of the reinforcement bars located near both faces in the lower part of the shell by 0.9.

Table 1: Material parameters

CONCRETE		
E_c= 2600 kN/cm^2	Tensile Strength	f_{tu}= 0.18 kN/cm^2
ν_c= 0.20	Compressive Strength	f_{cu}= 2.25 kN/cm^2
E_S= 2000 kN/cm^2	Coeff. of Therm. Exp.	$\alpha = 10^{-5}/^oC$
STEEL		
E_{ST}= 206000 kN/cm^2	Yield Stress	σ_y^{ST}= 40.0 kN/cm^2

2.3 Considered Load Cases

The investigation of the influence of the thermal preloading on the limit of serviceability and on the ultimate load of the structure comprises several thermal load histories. Two load cases refer to winter conditions. They are characterized by the incremental increase of the temperature difference ΔT_W - the subscript "W" stands for "winter" - between the inside and the outside surface up to 45°C (LOAD CASE II) and, for one of these two load cases (LOAD CASE III), by subsequent thermal unloading. Thereafter, the wind load w according to [3] is applied incrementally. These load histories may be written symbolically as

$$g + \Delta T_W/h + \lambda w \quad (LOAD \quad CASE \quad II), \tag{1}$$

$$g + \Delta T_W/h - \Delta T_W/h + \lambda w \quad (LOAD \quad CASE \quad III), \tag{2}$$

where g represents the dead load, h is the thickness of the shell and λ is a dimensionless parameter ($\lambda \geq 0$). For the purpose of including a possible weakening of the structure due to (micro)cracks on the inner surface, one additional load case (LOAD CASE IV) was considered. It allows simulation of a winter-summer cycle ($\Delta T_W = 45°C, \Delta T_S = -20°C$) with subsequent thermal unloading prior to the incremental application of the wind load:

$$g + \Delta T_W/h - \Delta T_W/h + \Delta T_S/h - \Delta T_S/h + \lambda w. \tag{3}$$

In order to assess the stiffness reduction due to the observed cracks, an ultimate load analysis of the originally uncracked shell was performed (LOAD CASE I):

$$g + \lambda w. \tag{4}$$

3. INFLUENCE OF THE THERMAL LOAD HISTORY

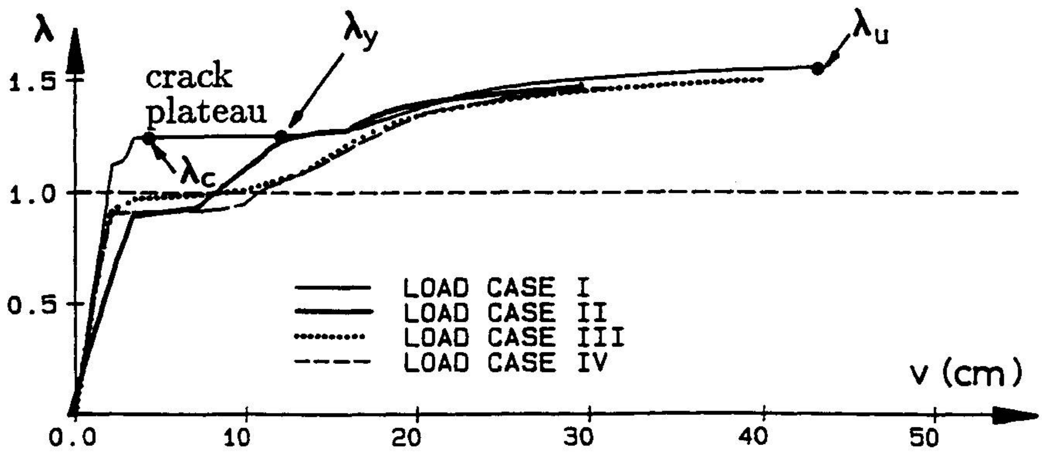


Figure 2: Load-displacement curves for load cases I, II, III and IV

In Fig.2, the horizontal displacement at the windward meridian, at the crown of the shell, parallel to the axis of symmetry (see Fig. 1b) is plotted as a function of the dimensionless factor λ for the load cases I, II, III and IV, respectively. Obviously, the damage induced by thermal preloading (LOAD CASES II, III and IV) has a significant influence on the level of the "crack plateau" (λ_c). With respect to the ultimate load level (λ_u), however, the influence of these temperature cracks is insignificant. The beginning of yielding of the reinforcement (λ_y) may be considered as a *sufficiently conservative limit of the serviceability* of the structure. Compared to the uncracked structure, the values for λ_y obtained from analyses of the damaged shell ($\lambda_y = 1.24$ for LOAD CASES II and III and $\lambda_y = 1.20$ for LOAD CASE IV) are only sligthly lower than $\lambda_y = 1.29$, corresponding to LOAD CASE I. Table 2 summarizes the values for λ_c, λ_y and λ_u resulting from the numerical investigation.

Table 2: λ_c, λ_y and λ_u for load cases I, II, III and IV

Load Case	λ_c	λ_y	λ_u
I	1.26	1.29	1.56
II	0.92	1.24	1.495
III	0.98	1.24	1.515
IV	0.915	1.20	1.47

It is noteworthy that the mode of considering the history of the temperature loading does not have a great influence on the structural resistance of the shell when being subjected to wind loading.

4. INFLUENCE OF CORROSION

In the investigation described so far, corrosion of the reinforcement was considered by multiplying the diameter of those reinforcement bars by 0.9, which are located near both surfaces at the lower part of the shell. This assumption was regarded as not sufficiently conservative. Therefore, three different

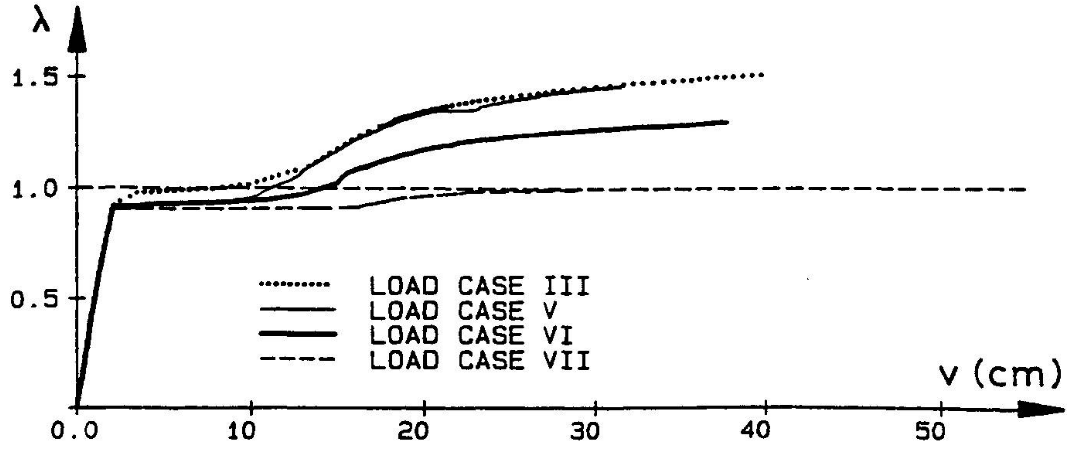


Figure 3: Load-displacement curves for load cases III, V, VI and VII

assumptions were made concerning the amount of corrosion that may occur in the remaining lifetime of the cooling tower. (The temperature loading process was chosen according to LOAD CASE III). In LOAD CASE V, only corrosion of the reinforcement bars located near both faces of the lower part of the shell is considered. According to [5], a reduction of the diameter of the reinforcement bars by 0.1 mm per year is a realistic assumption. Hence, after 25 years, the total reduction of the diameter will be 2.5 mm. In LOAD CASE VI, also the corrosion of the reinforcement bars located in the middle of the shell is taken into account. The diameter of these bars is multiplied by the factor 0.9. LOAD CASE VII is based on the worst assumption. Corrosion is considered by a 2.5 mm reduction of the diameter of *all* reinforcement bars.

Fig.3 contains load-displacement diagrams obtained from LOAD CASES III to VII. The respective values for λ_c, λ_y and λ_u are summarized in Table 3.

Table 3: λ_c, λ_y and λ_u for load cases III, V, VI and VII

Load Case	λ_c	λ_y	λ_u
III	0.98	1.24	1.515
V	0.925	1.21	1.465
VI	0.93	1.07	1.30
VII	0.905	0.915	0.995

For LOAD CASE VI, λ_y and λ_u are obtained as 1.07 and 1.30, respectively, as compared to 1.24 and 1.515 for LOAD CASE III. For LOAD CASE VI the ratio $\lambda_u/\ \lambda_y$, is equal to 1.22. In view of the character of this ratio as a "residual safety factor", the reduction of the diameters of the reinforcement through multiplication of the diameter by 0.9, as considered in LOAD CASE VI, can be regarded as a tolerable *upper limit* for the corrosion. For a significantly worse state of corrosion, as represented by LOAD CASE VII, almost no safety margin between the cracking plateau and the onset of yielding exists. This load case represents a critical state of corrosion, where neither safety against loss of serviceability nor against structural failure is guaranteed! Such a critical state of corrosion of the reinforcement located in the middle of the shell, however, is unlikely to occur.

5. INFLUENCE OF THE TENSILE STRENGTH

The sensitivity of the structural response with respect to the assumed value for the direct tensile strength f_{tu} is demonstrated by reinvestigating LOAD CASE VI, on the basis of the experimentally obtained value $f_{tu} = 0.26\,kN/cm^2$ (LOAD CASE VIII) instead of the original value $f_{tu} = 0.18\,kN/cm^2$. Table 4 contains the values for λ_c, λ_y and λ_u for the two load uses. For an increase of the tensile strength by 44.4 %, λ_c increases by 28 %, λ_y by 13 % and λ_u by 2.7 % !

Table 4: λ_c, λ_y and λ_u for Load Cases VI and IVII

Load Case	λ_c	λ_y	λ_u
VI	0.93	1.07	1.30
VIII	1.205	1.21	1.335

6. CONCLUSIONS

It is concluded that the investigated cooling tower shell will be sufficiently safe against structural failure even if no provisions for a repair of the concrete shell are taken, provided the reduction of the diameter of the reinforcement bars will be less than 10 % within the remaining life-time of the structure. The degree of corrosion of the reinforcement and, consequently, the efficiency of the precautions taken to protect the reinforcement from further corrosion are the relevant criteria for the safety of the cooling tower against loss of serviceability and structural collapse.

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