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Numerical Analyses and Strengthening of Reinforced Concrete Structures

Analyses numériques et réparation des constructions en béton armé

Die Rolle numerischer Analysen bei der Sanierung von Stahlbetonbauwerken

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SUMMARY

The role of nonlinear finite element analyses in the design process of the repair of damaged reinforced concrete structures is illustrated in the context of the strengthening of a damaged cooling tower shell. The effectiveness of the repair by attaching stiffening rings to the shell is demonstrated by means of numerical simulations using realistic material modelling based on the state of damage of the structure.

RÉSUMÉ

Le rôle des méthodes non-linéaires par éléments finis en liaison avec le projet et la réparation des constructions en béton armé est décrit, en particulier dans le cas d'une tour de refroidissement fissurée. L'efficacité de la réparation avec des anneaux renforcés est démontrée par des simulations numériques utilisant des modèles constitutifs réalistes, tenant compte de la détérioration de la structure.

ZUSAMMENFASSUNG

Die Rolle nichtlinearer Finite Elemente Analysen bei der Sanierung von Stahlbetonbauwerken wird anhand der Verstärkung einer durch Risse geschädigten Kühlturmschale aufgezeigt. Die Wirksamkeit einer Sanierung durch Versteifungsringe wird mit Hilfe numerischer Simulationen unter Verwendung wirklichkeitsnaher Materialmodelle und unter Berücksichtigung der Vorschädigung demonstriert.

1. MOTIVATION

Reinforced concrete (RC) structures, designed and constructed in the 1950s and 60s, frequently show signs of damage, such as cracks, which, in general, are caused by stresses that were not considered adequately by the design provisons of that time. Typical examples are reinforced concrete shells, showing meridional cracks due to bending stresses, induced by temperature gradients [1], [2]. If such a state of damage is observed, the question arises, whether a repair is technically and economically feasible, and, in case a repair is taken into consideration, how to design suitable provisions for the strengthening of the RC structure. Here, the term "optimality" is defined as the most economic design which guarantees sufficient structural safety within the anticipated lifetime. For many complex structures the answer to this question can only be obtained by means of modern analysis tools such as the Finite Element Method (FEM). This paper adresses the role of the FEM in the context of the design of the repair of a cracked cooling tower constructed in 1964. The sequence typically followed in the design procedure involving realistic numerical simulations is discussed and illustrated by means of this specific example.

The dimensions of the cooling tower are illustrated in Fig.2. The nominal shell thickness is 10 cm. Its present state is characterized by an approximately uniform distribution of long, meridional cracks caused by thermally induced stresses (Fig.1). Details of the numerical analyses of the restoration of this cooling tower are published elsewhere [2], [5].

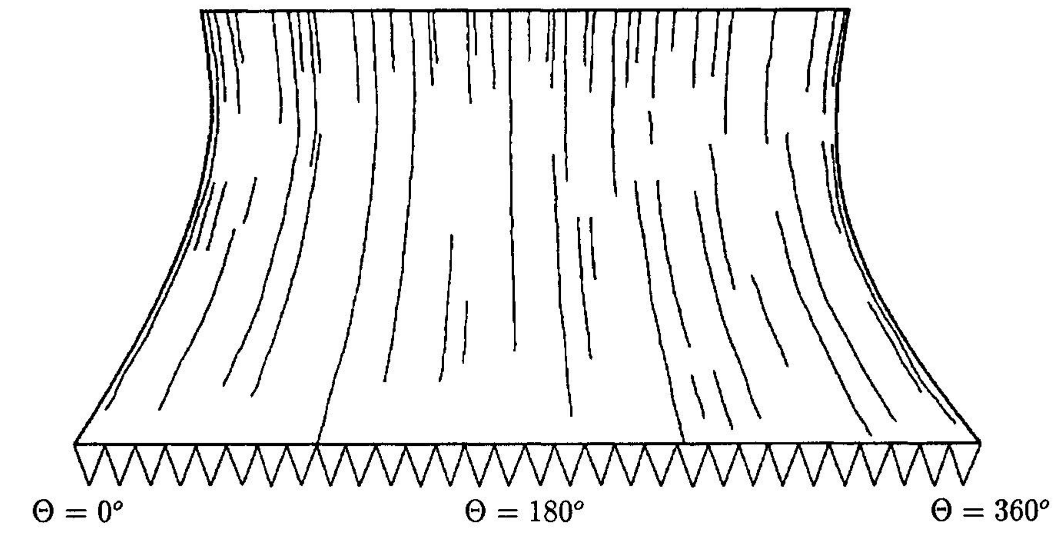

Figure 1: Distribution of Cracks at the Outside Surface of the Cooling Tower Shell

2. ASSESSMENT OF STATE OF DAMAGE

As a preliminary step in the design process of a damaged RC-structure, a thorough assessment of its present state by means of a survey and of laboratory investigations is necessary. In the reported investigation, the spatial distribution has been obtained from a detailed inspection of the shell and the opening of cracks (crack width ranging between 0.1 to 2.7 mm), the state of corrosion of the reinforcement located at cracks or in their vicinity (reduction of diameter ranging from 11 % to 30 %) and the actual thicknes of the cooling tower shell (thickness varying between 7.6 cm and 10.2 cm) were obtained from specimens taken from different locations of the shell.

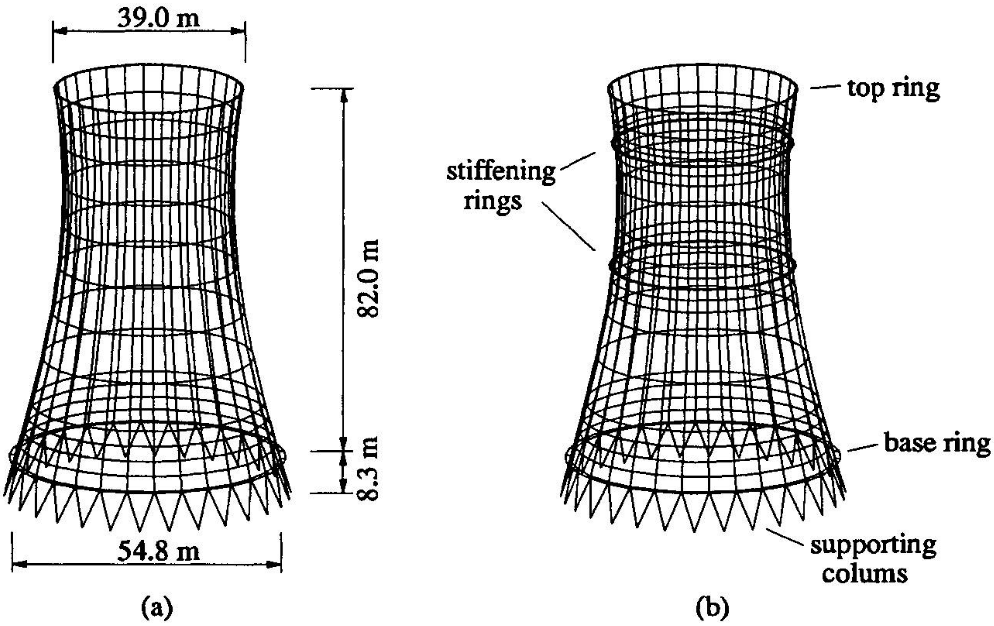

Figure 2: FE–Meshes: (a) Coarse, (b) Fine

3. SELECTION OF COMPUTATIONAL MODEL

The selection of an appropriate computational model depends on the degree of sophistication necessary for a realistic representation of the damaged (and restored) state of the structure. In this context, the element type (truss or beam elements, plate or shell elements, 3D elements), the numerical procedure (geometrical and physical nonlinearity, displacement or non-standard methods, etc.), the material model (elasticity, elasto (visco-) plasticity, damage theory etc.) needs to be specified.

In the presented example, an updated-Lagrangian FE-approach based on isoparametric thick-shell elements subdivided into 13 layers is employed. Fig. 2 contains two FE meshes used at different stages of the numerical investigations. The spatial distribution of the initial cracks is unsymmetric. Hence, specification of symmetry conditions would have been inadmissible. The numerical representation of cracked concrete is based on the "fixed crack" concept in the context of the "smeared-crack" approach. Cracks will begin to open normal to the direction of the maximum principal stress, if this stress reaches the tensile strength. Secondary cracks are restricted to the direction perpendicular to the primary cracks [5]. The ductile behavior of concrete under compression is accounted for by an elastoplastic strain-hardening Drucker-Prager material model. In the numerical investigations the reinforcement (meridonal and circumferential bars) is represented by mechanically equivalent, thin layers of steel with only an axial stiffness in the respective direction. A linearly elastic, ideally plastic constitutive law is assumed [5].

4. NUMERICAL REPRESENTATION OF DAMAGE

The numerical representation of the damaged state of the investigated structure may either be accomplished through modification of the respective geometrical data and model parameters or by re-analysis of the process which presumably has caused the observed state of damage. For the purpose of determination of the safety coefficient of the structure before and after its repair, the expected residual lifetime of the structure needs to be defined. Moreover, prognoses of the state of damage at the end of the expected lifetime should be made. Generally, this results in several scenarios for the present and the future state of damage of the structure, involving "worst case" and "mild" assumptions for the expected damage evolution.

In the considered example, the meridonal cracks are accounted for in the FE-model by a reduction of the concrete tensile stress at the integration points in the vicinity of these cracks. The opening of the cracks is then triggered by the application of a thermal load history prior to applying the standard wind load [4]. This wind load is multiplied with a dimensionless factor λ which is increased incrementally [2]. The temperature load induces a nonuniform crack pattern which corresponds to the crack distribution obtained from the survey. The investigation of several damage-scenarios results in a present state and an anticipated state of damage at the end of the residual lifetime of the structure in the year 2018. This includes "mild" and "worst case" assumptions for the state of cracking (crack depth, crack width) as well as for the corrosion of the reinforcement.

5. DETERMINATION OF THE SAFETY COEFFICIENT OF THE UNRESTORED STRUCTURE

Before deciding on a repair of the structure, the coefficient of safety of the unrestored structure has to be evaluated. Here, the term "safety" is defined according to the type and the utilization of the building and to respective regulations [3], [4]. In particular, different safety factors with regards to the limit of serviceability and the ultimate load have to be considered. For realistic numerical simulations of damaged RC structures, the actual safety margin required within the residual lifetime depends on the reliability of the experimental data and of the underlying assumptions for the different scenarios of the present and future state of damage. As far as a critical interpretation of the numerical results is concerned, the influence of the chosen discretization has to be taken into account.

The assessment of the structural safety of the cooling tower shell is based on three dimensionless factors λ_c, λ_y^S and λ_u. Herein λ denotes the wind loading according to BTR [4]. λ_c refers to the level of the crack plateau, λ_y^S to the beginning of yielding of the reinforcement of the shell, which may be regarded as a sufficiently conservative limit of serviceability of the structure, and λ_u to the ultimate load-carrying capacity (Fig. 3). Taking into consideration that the serviceability of the cooling tower is not severely influenced by moderately large deformations, the decision for a repair was based upon λ_u. In a preliminary investigation the relevant load case including the most critical direction of wind loading was determined. Among the different aspects of damage, the corrosion of the reinforcing bars was found to be the determining factor for the structural safety within the anticipated lifetime. From the average value of $\bar{\lambda}_u = 1.035$, obtained as the coefficient of safety against structural collapse in the year 1993, and the corresponding average value of $\bar{\lambda}_u = 0.951$ representing the coefficient of safety against structural collapse in the year 2018, it was concluded that the cooling tower shell will not be suffiently safe against structural collapse for the remaining lifetime of 25 years unless provisions for a repair are taken.

6. SPECIFICATION OF REPAIR PROVISIONS

A suitable strategy for the strengthening of the structure must be developed on the basis of engineering judgement and of the safety levels obtained from the simulations of the unrepaired structure. Very often, the access of the building or the maintenance of production required during the construction play a crucial role in the decision for a specific repair procedure. As will be shown below, the effectiveness of the repair may be optimized in the sense of minimum

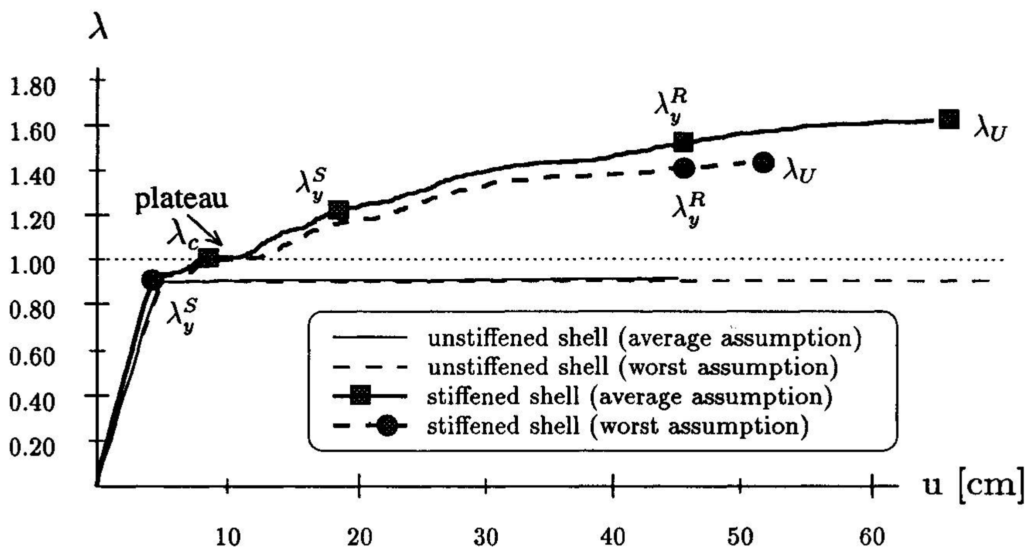

Figure 3: Load-Displacement Curves for Load Case Wind

costs while ensuring suffient structural safety by means of comparative numerical simulations. In general, the costs for advanced simulation techniques are by far compensated by savings from a FEM-supported design of the repair.

For the cooling tower shell, a repair by attaching reinforced cast-in-situ concrete stiffening rings was considered as the only feasible means of repair. In an extensive numerical study the influence of the number and the location of the stiffening rings upon the structural safety of the restored cooling tower was analyzed. The optimum position of one single ring was determined first. The location of a ring 52.0 m above the base has turned out to be most effective, resulting in an increase of the value λ_u for the unstiffened shell of 33.5 %. Next, combinations of two and three stiffening rings were investigated. For two stiffening rings located at levels of 70.0 m and 43.0 m above the base of the concrete shell, the increase of the collapse load is 73.1 %. Three stiffening rings (at levels 70.0 m, 52.0 m and 32.0 m above the base of the shell) cause an increase of λ_u by 107.0 %. As a conclusion from the comparative investigation, the use of two stiffening rings was found to be the best choice for the repair of the cooling tower shell. It will result in an increase of the maximum sustainable gradient wind load from $\bar{v}_G = 135.0$ km/h to $\bar{v}_G = 167.4$ km/h.

7. DESIGN OF STRENGTHENING ELEMENTS

Following the numerical optimization of the repair of the structure, the strengthening elements need to be designed and subsequently modified according to an iterative dimensioning procedure, involving re-analyses of the structure which, in general, is modelled by a refined FE–mesh.

For the repair of the cracked cooling tower shell, the final design of the cast-in-situ concrete rings (Fig. 4) was obtained from an iterative dimensioning process based on the refined mesh shown in Fig. 2b. The rings are bolted to the shell by "automatic undercutting bolts" (Figure 4). For the transfer of the forces from the shell to the ring it was assumed that shear stresses are transmitted by friction and that the axial forces are transferred by the bolts, connected with stirrup bars by means of threads, respectively. This assumption requires that the contact surface between the shell and the stiffening rings is adequately prepared in order to enhance friction in this surface.

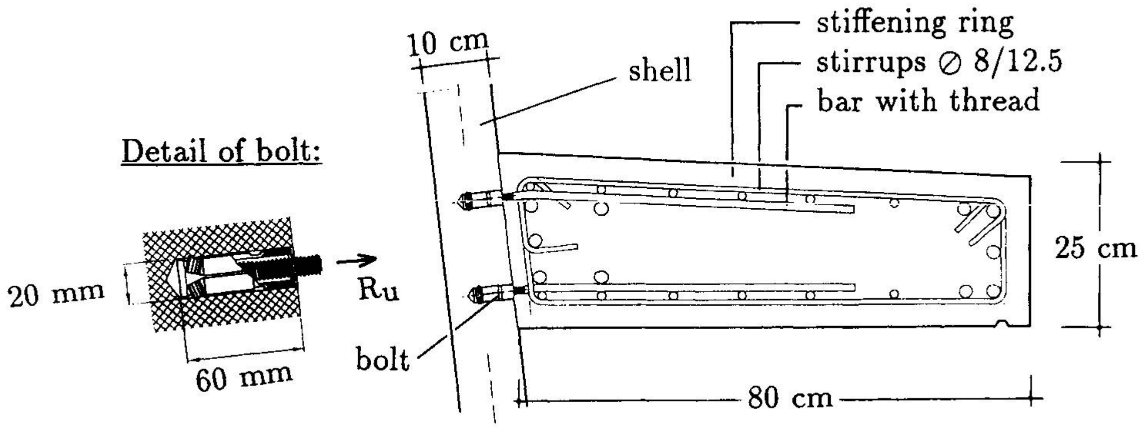

Figure 4: Typical Cross-Section Through Stiffening Ring

8. CONCLUSIONS

The role of sophisticated numerical modelling in the design of repair of RC structures was investigated in general. In particular, this role was illustrated in the context of the strengthening of a cracked cooling tower shell. It was shown that advanced simulation techniques based on realistic material models and on an adequate representation of the observed state of damage may be used for a relatively precise assessment of the residual structural safety. It is further concluded that advanced numerical analyses may be successfully employed to obtain a very economic means of repair. In case of the investigated cooling tower, the economic efficiency is characterized by the small number of stiffening rings required to guarantee a sufficient level of safety.

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