Computational mechanics and natural-draft cooling towers: from struggle for safety to designed lifespan

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Abstract

When natural-draft cooling towers started to exceed tower heights of about 100 m in the early 1960s, they turned out to be the most unsafe existing engineering structures: within less than 20 years, worldwide at least 10 towers were lost out of approximately 100. Nearly none of the deadly problems was known in detail at that time: internal stress distributions, influences of meridional shape, role of sufficient shell thickness and of double layer reinforcements at both faces, adequately stiff edge members, shape imperfections, effects of wind dynamics. It was a severe struggle to introduce into design and detailing of cooling towers more advanced structural mechanics and computational concepts. But only by such tools tower safety could be increased; they further contributed to the challenge of durability and to designed service lives. This presentation addresses some mentioned aspects and focusses on the use of modern computational concepts for increased safety and reliability, mainly related to the design of the largest tower in the world, the 200 m high tower at the RWE Power Station at Niederaussem, situated some 30 km west of Cologne in Germany.

Keywords: Cooling tower; Tower design; Structural safety; Structural damage; Lifespan

1. Introduction

Large natural-draft cooling towers serve as cooling devices mainly at steam power stations. At the end of their turbines, the 'worked-off' steam has to be condensed back to water and is reused in the boiler, subtracting from it the waste heat by use of cooling water. Instead of using natural water resources therefore, and thus polluting rivers, lakes or seashores with that waste heat, a cooling tower provides a permanent flow of cooling water and thereby releases the waste heat directly into the air. These huge engineering structures thus balance investment and operational costs of power stations for a reliable electric energy supply with demands for a cleaner environment.

In a natural-draft cooling tower, as shown in Fig. 1, warm cooling water from the turbine's condenser is distributed evenly through channels and pipes above the fill. As the water flows and drops down the fill sheets, cooler rising air there creates evaporative cooling, and the cooled-down water then is collected in the water

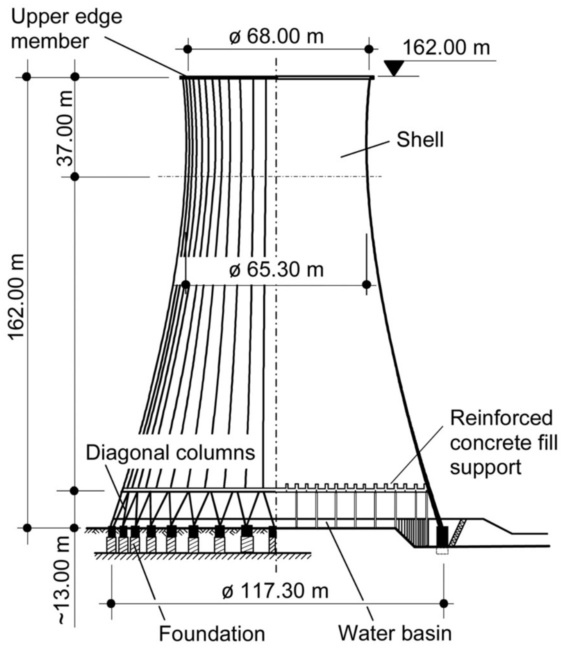

Fig. 1. Natural-draft cooling tower (Mülheim-Kärlich, Germany).

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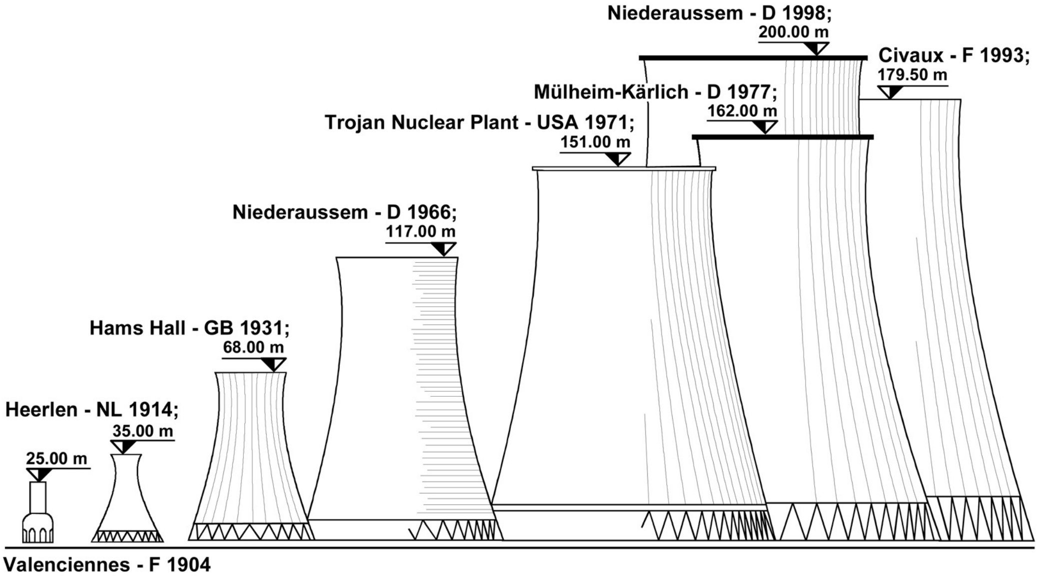

Fig. 2. Historical development of RC natural-draft cooling towers.

basin. The difference in density of the warm air inside the tower and the colder air outside creates the natural draft, which permanently sucks fresh air into the tower. The huge reinforced concrete (RC) shell only serves as protection of the continuing up-streaming air against atmospheric turbulence.

Figure 2 gives an impression on the rapid growth of RC natural-draft cooling towers in the last century, corresponding to the growth of power stations and their increase in degrees of efficiency. This evolution was accompanied by a series of tower collapses: Ferrybridge (UK, 1965), Ardeer (UK, 1973), Willow Island (USA, 1978), Bouchain (France, 1979), Missisippi (USA, 1981) and Fiddler's Ferry (UK, 1984). For the last 25 years, RC cooling towers have been considered as sufficiently safe, following an enormous amount of worldwide research in all fields related to safety and reliability of these structures. At present, the highest tower in the world is 200 m. This tower belongs to the new lignite power block of the RWE Power Station, Niederaussem, the huge tower at the front in Fig. 3. The reason for this enormous height is the size of the power block of 965 MW (net capacity), struggling for higher degrees of efficiency in order to save lignite fuel.

Fig. 3. Aerial view of the RWE Power Station at Niederaussem in summer 2001.

2. Linear design analysis and safety concept

Already before and increasingly shortly after the Ferrybridge disaster 1965 [1], in which three towers failed in obviously the same manner, wind tunnel investigations cleared the (quasi-static) wind loading W on these structures. Wind pressure has a typical circumferencial distribution, with compression around the stagnation pressure at the windward meridian, and two large suction areas on both flanks [2]. The maximum suction depends on the tower-face roughness. This typical distribution governs the linear tower response. Besides wind forces W and the important dead loads D, cooling towers are charged by service temperatures ΔT, often by soil settlements S and occasionally by seismic effects E.

These loading conditions act on the tower structure, which has to resist them within the design specifications. The German code for cooling towers [2], one of the earliest codes (1967) using partial safety factor design, proposed (as one of several) the following load combination:

$$D + 1.75W \leq R$$

Following the new unified European codes, here EC 2 [3], this has been changed to

$$0.90D + 1.60W \leq R/\beta_m$$

This combination (as several others) guarantees a probability of failure of $P_f < 10^{-4}$, a value considered as sufficiently small for this type of power station component. In both conditions R denotes the structural resistance in terms of yield stress with different material safety factors $\beta_{ms} = 1.15$ for reinforcement steel and $\beta_{mc} = 1.50$ for concrete.

Design and detailing of the cooling tower is generally based on internal stresses gained by quasi-static, linear finite element (FE) analysis, using integrated models with several thousand degrees of freedom (dof). For the design of the Niederaussem tower we have selected a FE model with 50,919 dof, including columns, foundation and parts of the soil, see Fig. 4. Before the final FE analysis, the meridional shape of the cooling tower shell and the stiffness of both edge members are pre-designed such that the dynamic actions in the structure, due to wind gales and probable earthquakes, are at a sufficiently low level, as Fig. 5 elucidates. In Fig. 5 the left tower variant has a sufficiently stiff upper edge member, the right one not. This keeps all wind vibrations including bending effects small, an approved prerequisite for structural durability.

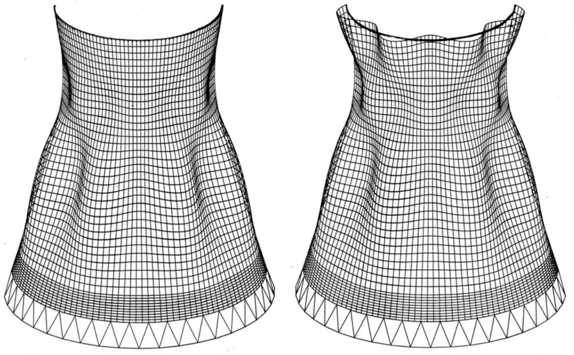

Fig. 5. Natural vibrations with stiff (left) and weak (right) upper edge member.

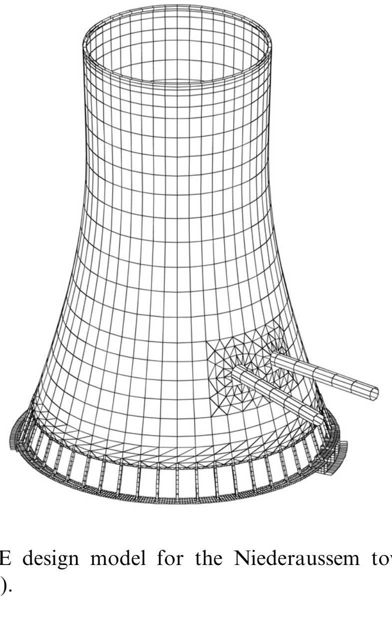

Fig. 4. FE design model for the Niederaussem tower (20% resolution).

3. Design for durability

Clearly, durability of a certain structure is a prime function of the construction material. But for highly stressed industrial structures, such as cooling towers, durability also requires a way of minimizing the stress level in general and of tension-cracking in particular. So for towers of extreme height, the meridional shape of the shell and its thickness has to be designed such that stresses due to dead weight D and wind W reach minimum values, especially all tension stresses. This is achieved by an optimization process of the hyperbolic meridian of the tower shell, and the result for the Niederaussem tower can be seen on Fig. 6 [4,5]. The shell

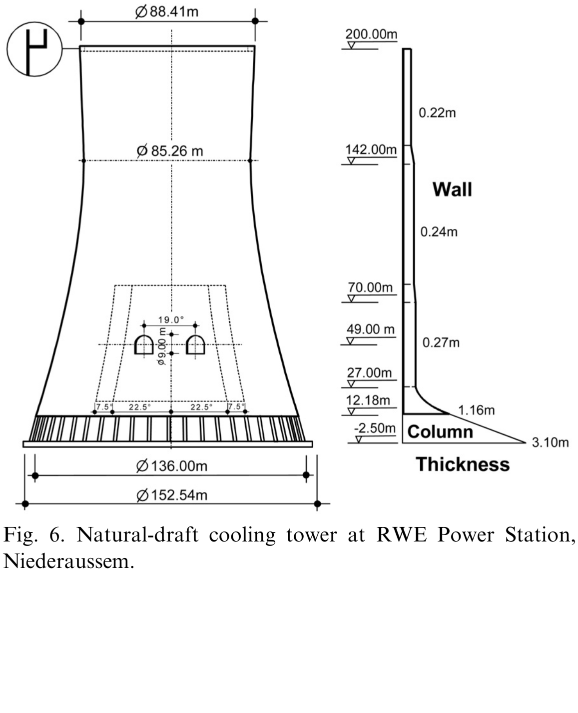

Fig. 6. Natural-draft cooling tower at RWE Power Station, Niederaussem.

meridian is represented by two hyperbola branches which are offset from the tower axis and meet at the throat. Using $r(z)$ for the distance from the tower axis to the shell middle surface,

$$\mathrm{r(z)} = r_{\mathrm{o}} + a\sqrt{\{1 + (H_T - z)^2/b^2\}},$$

both curves are described by the following parameters: $r_{\mathrm{o}} = -1.0730\,\mathrm{m}$, $a = 43.7030\,\mathrm{m}$, $b = 105.5967\,\mathrm{m}$, $H_T = 142.000\,\mathrm{m}$ below the throat, and for $r_{\mathrm{o}} = 42.3828\,\mathrm{m}$, $a = 0.2472\,\mathrm{m}$, $b = 7.9419\,\mathrm{m}$, $H_T = 142.000\,\mathrm{m}$ above it. These parameters result in an inclination of the shell middle surface just at the top of the supporting columns of 17.8°. In Fig. 6, the two holes in the shell serve as pipe inlets, releasing the cleaned flue gases into the vapor, and the area around the holes is thickened and reinforced considerably up to its initial stiffness [4,5].

The next step is the evaluation and, further, the iterative reduction of the crack-damage in the shell (by re-distribution of the original reinforcement), since mechanical cracking may start several specific deterioration processes in the concrete. For this purpose, nonlinear computer simulations based on damage-oriented material laws for reinforced concrete are applied [6]. Such highly sophisticated simulation techniques [7] use layered shell elements, and – for saving of computing time – a considerably reduced number of degrees of freedom, namely here 4,222. These techniques admit the evaluation of materially nonlinear responses including the crack-formation in the shell. Figure 7 depicts load-deformation paths for the maximum deflection in the throat area for different load combinations. Then from natural vibrations, superposed upon the different nonlinear deformed and damaged structural states, natural vibration frequencies f_i are computed, which serve as basis for formulation of damage indicators [8,9]:

$$D_i = 1 - f_{i,\mathrm{damaged}}/f_{i,\mathrm{damaged}}$$

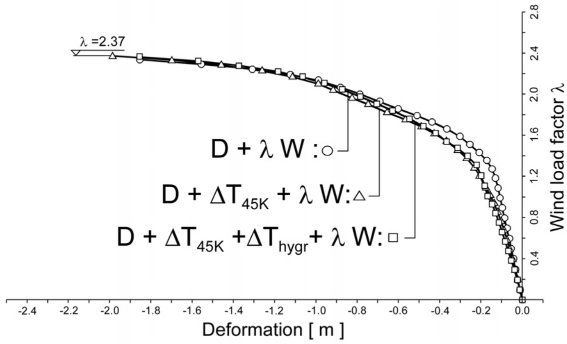

Fig. 7. Load-deflection paths in the throat for three load combinations.

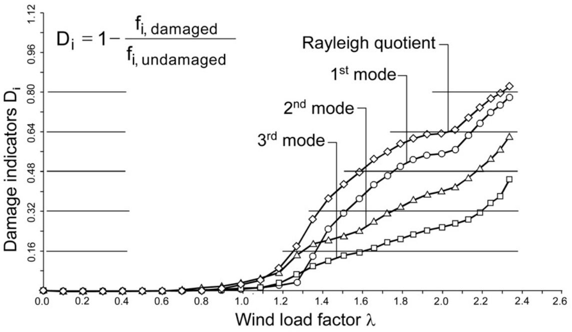

Fig. 8. First three damage indicators for the load combination $G + \lambda W$.

Figure 8 shows the first three damage indicators D_1, D_2 and D_3 for the finally executed shell of the Niederaussem cooling tower, for the load combination $G + \lambda W$ after iterative re-distribution of the original reinforcement in areas of early crack formation. One observes that under $G + \lambda W$ nearly no crack damage will appear until $\lambda \approx 1.00$, a design wind speed with a return period of 50 years.

4. Lifetime simulations

The service life of a power station is around 50 years, since several of their components, such as the turbine, are designed for such a lifespan. What about the cooling tower? And how to 'design' the cooling tower for an intended lifespan? As we have observed, such a structure is stressed by service temperatures ΔT, occasionally attacked by gales W, and after some initiation time deteriorated by a variety of chemical processes. If the effects of all these processes are modeled in the computer analysis, combined again with the nonlinear material model of RC mentioned already in Section 3, we are able to derive statements on the expected lifespan of the structure.

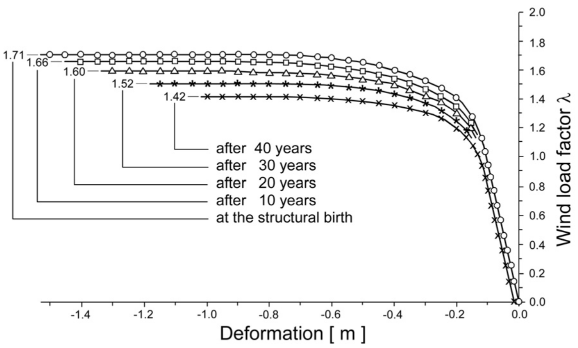

Fig. 9. Decrease of failure load factors over 40 years.

Figure 9 describes the results of such a life-cycle simulation [8,9], carried out for an elderly tower that had been in service for 28 years. The simulation starts with an initial gale of $\lambda = 1.22$, corresponding to a storm with a return period of ≈ 100 years. Such a gale will lead to some local crack damage. If a new (stronger) gale appeared, failure of the tower would happen at $\lambda = 1.71$, as indicated in Fig. 9. The previously mentioned cracking, if it touches the shell reinforcement, will start a corrosion process there, which is estimated by the computer simulation as a loss of 1% of the cross-section of the bars per year. Furthermore, the condensation of the vapor in winter starts a corrosion process of the concrete on the inner shell face, which is modeled simultaneously by a thickness loss of 0.6 mm/a. Both corrosion processes are considered, together with new gales of $\lambda = 1.00$ each tenth year. Also, again each tenth year, the maximum gale leading to failure of the already damaged tower is evaluated, and the reduced wind load factor λ can be found in Fig. 9.

As one observes from these results, the maximum wind load factor λ leading to structural failure at the monitored time falls from $\lambda = 1.71$ to $\lambda = 1.66$ and finally to $\lambda = 1.42$, after an interval of 40 years. Therefore, because of our safety codes [2], this tower then would be considered as unsafe, unless it underwent refurbishment long before the end of its intended service life [10].

5. Final remarks

Natural-draft cooling towers as civil engineering structures in general are designed in accordance with codes, which in most cases only consider their virgin structural state. But such structures may be highly stressed by gales causing crack damage, and they are subjected to typical deterioration (corrosion) processes over their lifetimes, all of which reduce the structure's safety and lifespan. This presentation demonstrated how modern concepts of computational mechanics form suitable advanced tools for simulation of these processes, for estimation of safety reductions, and by design responses to improvements of the structure.

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