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Large shell structures for power generation technologies

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Abstract

In power generation industries large RC shell-like structures are well in use, as safety containments for LNG tanks, shafts for wind generators, smoke stacks, nuclear power plant containments, natural draft cooling towers, and in future solar upwind chimneys. Especially these last two types of shells form the largest shell structures in technology. Because of their size they are extremely exposed to storms and to seismic actions. Since attacked by environmental effects, the damage evolutions determine to a large extend their service-lives. Many structural phenomena, like forced vibrations, static and dynamic instabilities, or damage-induced failure, influence their safety and reliability. The present lecture will address some of these typical mechanical effects of large "wet" as well as "dry" natural draft cooling towers and for chimneys of solar upwind power plants.

1. "Wet" natural draft cooling towers

Due to the rising demand for cheap, economic as well as sustainable electricity, natural draft cooling towers (NDCT) at the "cold ends" of thermal power generation processes, have grown to enormous sizes and heights. Simultaneously, their shells developed to the largest reinforced concrete (RC) shell structures in technology. Compared to shell roofs or tanks, NDCTs are exposed on both faces to aggressive fuel combustion media. Additionally, aggressiveness in the towers' interiors is increased in Germany by release of cleaned flue gases therein, saving former customary smoke stacks (Krätzig *et al*. [3]).

So in addition to classical design conditions for load combinations of deadweight G, wind W, internal suction S, service temperature T, hygro-thermal attack H, and probably seismic actions E, durability is the key issue in the design of NDCTs. Possible structural shell repairs are limited to rather short shut-downs of the plant. Even in case of surfaces up to 60.000 m² each side for modern towers, sufficiently long shut-downs for careful surface repairs are illusionary.

The paper will report in detail on typical structural design efforts for cooling tower shells of extreme size, namely the shape optimization of the meridian, the construction of the flue gas inlet, the application of special acid-resistant high-performance concrete, and on design concepts to increase the shells' durability.

Here we describe the constituents of such huge wet NDCTs by example of the world-largest tower of 200 m of height at the RWE Power Station Niederaussem, some 20 km west of Cologne. Figure 1 shows the entire plant during construction in the year 2000. The new lignite power block BoA (left) has a net capacity of 965 MW, achieved by an efficiency of over 43%, the highest electrical net degree of efficiency of lignite fueled power plants worldwide. The 200 m cooling tower contributes considerably to this world record (Busch *et al*. [2]).

As confirmed in Figure 2, the total height of the cooling tower shell is 200 m. Its water basin diameter measures 152.54 m, that one of the lower shell rim 136.00 m, and the top opening is 88.41 m wide. Both the outer and inner shell faces measure about 60.000 m², equivalent to 10 soccer fields each. The tower shell is composed of two hyperbolic shells of revolution, meeting at the throat. It exhibits largely a wall thickness between 0.22 and 0.24 m, increasing towards the lower shell rim. The top edge of the shell is stiffened by an upper edge member with U-shaped cross-section, extending into the interior. The overhang measures 1.51 m with a shank-height of 1.20 m. To reduce crack-sensibility of the upper shell due to wind vibration, this edge member is pre-stressed by

Figure 1: Power Station Niederaussem (Photo RWE)

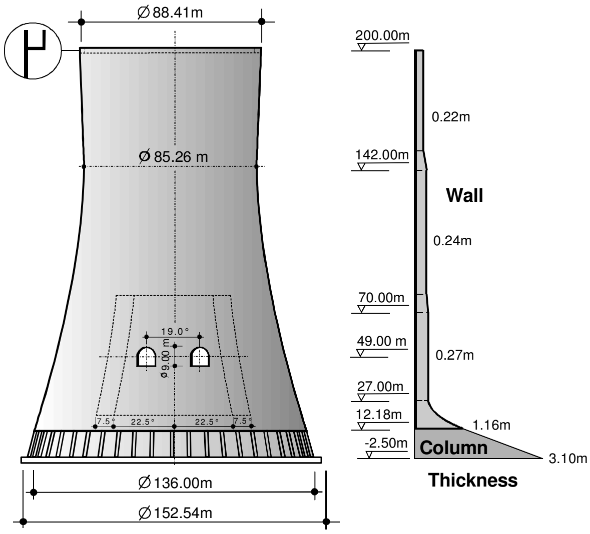

Figure 2: Dimensions of NDCT Niederaussem

4 SUSPA tendons with 8 mono-wires of 150 mm² cross-section each of steel quality St 1570/1770 N/mm². The lower edge member is formed by an increase of the shell thickness up to 1.16 m. The complete shell is made from acid-resistant high-performance concrete of compression strength of 85 N/mm², so-called ARHPC 35/85, to save a protective coating of the inner surface.

The cooling tower shell is supported by 48 meridional columns of 14.68 m of height, cast of RC 45/55 due to Eurocode EC 2. Their thickness ranges from 1.16 m on top to 3.10 m above foundation, their width is 1.40 m. All columns rest on a RC ring foundation of 6.60 m of width and 1.80 m of height. Softer soil than the standard consolidated gravel was exchanged. Along the water inlets and the water outlet the ring-width was enlarged.

All further tower components are conventional. The interior contains the water basin to collect the re-cooled water. Its basin plate and walls consist of water-proof RC 30/37 with 0.20 m of thickness, founded on a 0.15 m thick C 12/15 layer over an anti-freeze stratum of 0.30 m. The fill construction and the water distribution are designed as a prefabricated RC beam-column structure also made of high-performance concrete ARHPC 35/85.

The new Niederaussem power block BoA went into service in 2002, gaining excellent service experiences up to date. Presently, a series of new fossil fueled (lignite and hard coal) power stations is under design/construction in Germany since then, all with very similar NDCTs, and those common attributes mentioned at the beginning: Meridional shape optimization, cleaned flue gas release, ARHPC 35/85, design for durability. The lecture will present details of these attributes, and demonstrate design consequences of them, like preserving the original buckling safety, vibration properties and simulating the damage evolution over their life-times.

2. High "dry" cooling towers and low (mini) solar chimneys

Wet cooling systems consume cooling water through evaporation, as the vapor cloud above the tower indicates. If water consumption is unacceptable, "dry" cooling has to be chosen, in which the water is captured in a closed piping system. Then cooling works only by convection with lower efficiency, such that dry cooling towers have strongly enlarged dimensions. Already in the 1970ies large dry NDCTs were designed for power station in arid zones, reaching up to 300 m. With this height they approach low solar chimneys which start for professional operation at heights of approximately 500 m.

Figure 3 shows the design study of such a chimney. The tower has a total height of 500 m, diameters of 120 m at the throat and of 200 m at its base. The wall thickness increases from 0.25 m on the top to 0.60 m on the foundation slab. The shell with shape-optimized meridian requires a classical upper edge member and three intermediate stiffening rings. These stiffeners serve two important purposes,

- to reduce the buckling lengths of the shell for sufficient safety against instability failure,
- to constrain the meridional/shear forces in the shell due to wind towards a beam-like behavior.

The first purpose can be achieved with rather moderate sized cross-sections of all four stiffeners, attached on the shell outside, namely a hangover-width of 2.50 m and a thickness of 0.40 m. The second purpose requires stiffer rings in order to reduce the maximum wind tension towards the order of magnitude of the dead-load compression, an optimal design goal. With the above given dimensions, tension/shear stress maxima can be reduced up to 2/3. Higher reductions require internal spokes in the rings as recommended by (Schlaich *et al.* [4]).

Experienced designers of NDCT shells would attempt to construct the shell of Figure 3 without intermediate rings. The lecture will demonstrate for this case how the then globally extended instability modes require a thickness increase of the shell. Adding three sufficiently stiff intermediate rings, probably with spokes, as mentioned above lets the buckling safety of the shell grow by the factor 1.7.

3. Shells for future solar chimneys power plants

Due to Figure 4 Solar Chimney Power Plants (SCPP) consist of the glass-covered collector area, the turbo-generators for power conversion and the solar chimney. In the collector, solar radiation heats the collector ground and so warms up the enclosed air, which streams towards the center. There in the power conversion units, the energy of the air stream partly transforms into electric power, before being released through the chimney as pressure sink.

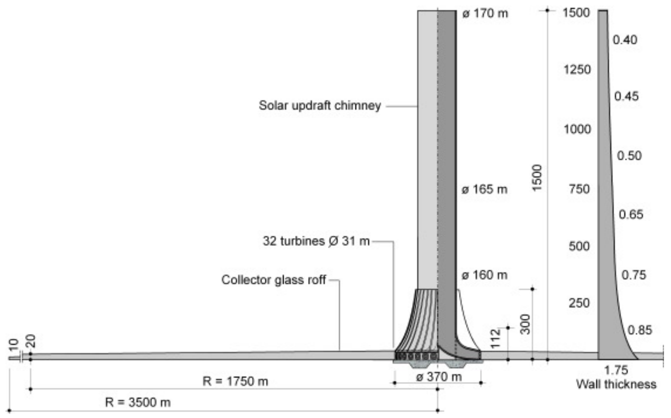

Figure 4: Overview over components of a SCPP

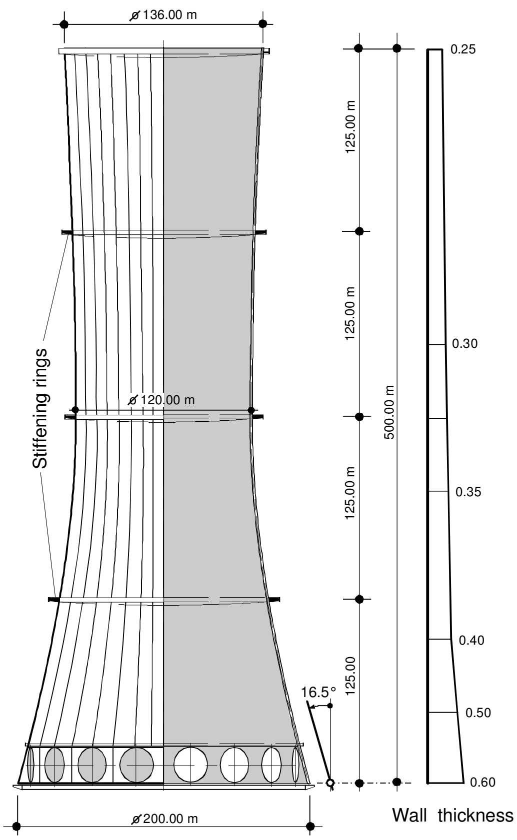

Figure 3: Solar tower of 500 m of height

SCPPs are the most sustainable natural resources for electric power generation. They copy the daily solar-thermal air motion in the atmosphere producing electric energy completely free of CO_2-emissions. However, up to date none SCPP has been brought to reality, except for one 50 kW-prototype, erected 1982 in Spain under the guidance of J. Schlaich (Schlaich *et al.* [4]), a pioneer of this technology. This prototype power station worked successfully for more than 6 years. The efficiency of such power generation depends mainly on the size of the collector area and on the height of the chimney, both reasons for the enormous dimensions of SCPPs: Collector diameters up to 7 km and chimney heights up to 1500 m are on pre-design. Figure 5 shows a collection of several possible solar chimneys, all compared to the highest natural draft cooling tower at Niederaussem.

From a load-carrying viewpoint, solar chimneys are extremely enlarged, over-dimensioned NDCT shells, demonstrating all those problems known to cooling tower designers from half a century of experience, namely:

- High compression stresses under deadweight D, wind action W and service temperature T,
- tendency to vertical outside cracking under D, W and T,
- high sensitivity to shell buckling instabilities under D, W and wind suction S,
- forced wind vibrations in the upper chimney part eventually leading to dynamic instabilities,
- strong sensitivity to soil-structure interaction phenomena,
- interestingly a natural safety margin against seismic actions because of low 1^{st} eigenfreqencies,
- stress and thermal fatigue phenomena of the required high-performance concrete,
- durability problems towards the end of a SCPP's service live duration (designed for 80÷120 years).

The structural design of such a solar chimney is an optimization process to compromise between several of these conflicting key points, as the presentation will point out (Backström *et al.* [1]). As example, Figure 6 shows the first three buckling modes for a 1000 m solar chimney with upper edge member and nine intermediate stiffening rings, designed for high performance RC 70/85.

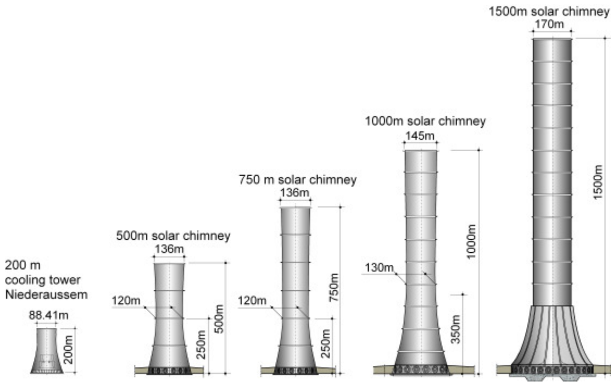

Figure 5: Solar chimneys of different height

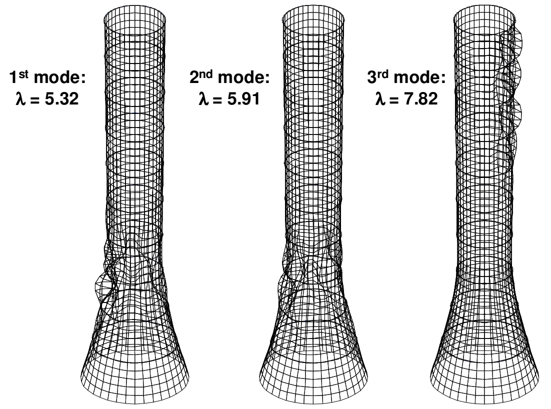

Figure 6: Buckling modes of 1000 m solar chimney

4. Summary

The presentation will illuminate the role of shell structures in power generation technology, in presence. Due to the worldwide rising consciousness for sustainable, CO_2-free energy production, this role is expected to grow enormously in future SCPPs.

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