Large shell structures for power generation technologies

1. Natural draft cooling towers and solar updraft chimneys: Why large?

2. Natural draft cooling towers:
   - Construction principles • loading and internal stress variables • shape optimization • instability and vibrations • damage and life-duration

3. Solar updraft power plant chimneys:
   - Construction principles • shell strength versus ring-stiffening • instability and vibrations

4. Conclusions
Thermal power plant with cleaned flue gas injection
Development of natural draft cooling towers
Actual cooling tower projects made of high-performance concrete in Germany
From natural draft cooling towers to solar chimneys
Solar GreenTower ® Competence Network

- **W.W. Stinnes** M.Sc.(Phys.), Haiger (Germany) und Pretoria (RSA)
- **Prof. Dr. R. Harte**, U. Wuppertal + Krätzig & Partner, Bochum
- **Prof. Dr. Dr. E.h. W.B. Krätzig**, Ruhr-University + Krätzig & Partner, Bochum
- **Prof. Dr. H.- J. Niemann**, Ruhr-Universität und Niemann & Partner, Bochum
- **Prof. Dr. D.G. Kröger**, University of Stellenbosch, RSA
- **Prof. Dr. T.W. von Backström**, University of Stellenbosch (RSA)
- **Prof. Dr. G.P.A. van Zijl**, University of Stellenbosch und T.U. Delft
- **Dr. V. Wittwer**, ISE Fraunhofer Institut für Solare Energiesysteme, Freiburg

**Prof. Dr. J. Meins**, T.U. Braunschweig

further research institutes and industrial enterprises from different countries
Annual global solar radiation (kWh / m²)

- Yellow areas – more than 1950 kWh / m²
- Red areas – more than 2200 kWh / m²

Schematic solar chimney power plant

Sun

Solar Chimney SC

Collector Area CA

Turbine

Generator coupled to the turbine PCU

Ground
Prototype solar chimney power plant
Manzanares, Spain (1982), prototype project Prof. J. Schlaich
Natural Hazard Resistant Design of the Green Tower

Solar Chimney

32 Turbine openings Ø 31 m

Collector roof

K & P 08/3-31  Krätzig & Partner Ingenieurgesellschaft für Bautechnik mbH
GreenTower Project Namibia: Tower foot alternative

32 Additional Stiffening Walls $d = 2.0\text{m}$

32 Turbines $\varnothing 31\text{ m}$
Artist’s view of large solar chimney power plant
Large shell structures for power generation technologies

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NDCT RWE Lignite Power Plant Neurath 2007
Collapses of natural draft cooling towers of more than 100 m of height

1965  Ferrybridge GB, 01.11.
1973  Ardeer GB, 27.09.
1978  Willow Islands USA, 27.04
      46 casualties
1979  Bouchain F, 30.08.
1981  Mississippi USA,
1984  Fiddler 's Ferry GB, 15.01.

1984  Worldwide ≈ 160 cooling towers of more than 100 m of height;
      Lost in 19 years: 8 towers ≈ 5%.
NDCT Goesgen: Aerial view
Monitored cracks of a cooling tower segment
Crack growth:
Accumulated lengths of monitored cracks
Pre-design NDCT Niederaussem: First eigenmode of virgin tower
Pre-design NDCT Niederassem:
First eigenmode at D + 1.4W
Wind load factor versus natural frequencies

\[ D + \Delta T_{45K} + \lambda W \]
Plane and open ground, WZ II Germany: \( v_m = 40.0 \text{ m/s} \), \( z = 100.0 \text{ m} \), \( L_{ux} = 225.0 \text{ m} \)

\[ S \cdot f / \sigma^2 \]

\[ D + \Delta T_{45K} + \lambda W \]

Karman spectral density function

- \( \Delta T = 45 \text{K}, W = 1.2 \text{ W} \)
- \( \Delta T = 45 \text{K}, W = 0.9 \text{ W} \)
- \( \Delta T = 45 \text{K}, W = 0 \)
- \( \Delta T = 0, W = 0 \)

Increase of Wind-Dynamics due to Cracking

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Ruhr - Universität Bochum • Statik und Dynamik

05 - 1-9
New challenges for cooling tower shells:

- Height of 200 m for environmental reasons
- High-performance concrete ARHPC 85/35
- Detailed shape optimization
- Design for durability
- Lifetime design for ~ 55 years
NDCT Niederaussem: Computer vision of new power station with existing blocks
Natural draught cooling tower at Niederaussem Power Station (Execution)
NDCT Niederaussem: Geometry of both edge members
NDCT Niederaussem: Geometry and material data of cooling tower (ARHPC 85/35)

Shell
\[ r = r_0 + \frac{a}{b} \sqrt{b^2 + (H_T - z)^2} \]

Lower shell:
- \( r_0 = -7.2435 \) m
- \( a = 49.8735 \) m
- \( b = 114.9326 \) m
- \( H_T = 142.00 \) m

Upper shell:
- \( r_0 = 42.3703 \) m
- \( a = 0.2597 \) m
- \( b = 8.2940 \) m
- \( H_T = 142.00 \) m

Columns
- \( \alpha = 72.0^\circ \)
- \( H_0 = 12.18 \) m
- \( H_u = -2.50 \) m
- \( W_o \cdot D = 1.16 \times 1.40 \) m
- \( W_u \cdot D = 3.10 \times 1.40 \) m

Steel: BSt 500 S
- \( E_s = 2.1 \times 10^8 \) kN/m²
- \( f_{ym} = 5.0 \times 10^5 \) kN/m²
- \( f_{tm} = 5.5 \times 10^5 \) kN/m²
- \( \varepsilon_{sh} = 0.02 \)
- \( \varepsilon_{su} = 0.01 \)

Concrete: C 85/35
- \( E_c = 4.04 \times 10^7 \) kN/m²
- \( \nu = 0.20 \)
- \( f_{cm} = 8.20 \times 10^4 \) kN/m²
- \( f_{ctm} = 2.88 \times 10^3 \) kN/m²
NDCT Niederaussem:
Basic dimensions for tower shape optimization

\[ r(z) = r_o + a \sqrt{1 + \frac{(h_T - z)^2}{b^2}} \]
\[ \tan \beta_L \geq \frac{(r_L - r_T)}{(h_T - h_C)} \]
Meridional Forces $n_{22g}$ under Deadweight

200 m Cooling Tower at KW Niederaussem

02 - 5-7

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Circumferential Forces $n_{11g}$ under Deadweight

200 m Cooling Tower at KW Niederassem

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24 Seconds of a storm profile
Lignite power station Neurath in boundary wind tunnel
Gust modeling in the wind tunnel
NDCT Niederassem: Types of circumferential wind pressure distribution $c (\Theta^1)$

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03-4-5
Meridional Forces $n_{22w}$ under Wind Actions

200 m Cooling Tower at KW Niederaussem

Wind Direction
Shear Forces $n_{12w}$ under Wind Actions

200 m Cooling Tower at KW Niederaussem

Wind Direction

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Circumferential Forces $n_{11w}$ under Wind Actions

200 m Cooling Tower at KW Niederaussem

Wind Direction

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NDCT Niederaussem:
Lowest natural frequencies for shells without / with holes and corresponding modes

\[ f_{\text{min}} = 0.7302 \text{ Hz} \quad f_{\text{min}} = 0.7335 \text{ Hz} \]
<table>
<thead>
<tr>
<th>Mode</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; mode</th>
<th>2&lt;sup&gt;nd&lt;/sup&gt; mode</th>
<th>3&lt;sup&gt;rd&lt;/sup&gt; mode</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><strong>G</strong></td>
</tr>
<tr>
<td>f</td>
<td>0.711</td>
<td>0.834</td>
<td>0.846</td>
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<td></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td><strong>G</strong> + ΔT&lt;sub&gt;45K&lt;/sub&gt;</td>
</tr>
<tr>
<td>f</td>
<td>0.593</td>
<td>0.682</td>
<td>0.790</td>
<td></td>
</tr>
<tr>
<td></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
<td><strong>G</strong> + ΔT&lt;sub&gt;45K&lt;/sub&gt; + 1.0 W</td>
</tr>
<tr>
<td>f</td>
<td>0.589</td>
<td>0.709</td>
<td>0.733</td>
<td></td>
</tr>
</tbody>
</table>

**NDCT Niederasussem:**
Change of natural modes due to crack damage

02 - 2-32

Ruhr - Universität Bochum * Statik und Dynamik *
### NDCT Niederassem:
Change of natural modes due to crack damage

<table>
<thead>
<tr>
<th>Load</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; mode</th>
<th>2&lt;sup&gt;nd&lt;/sup&gt; mode</th>
<th>3&lt;sup&gt;rd&lt;/sup&gt; mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f=0.586</td>
<td>f=0.590</td>
<td>f=0.715</td>
</tr>
<tr>
<td>G + ΔT&lt;sub&gt;45K&lt;/sub&gt; + 1.2 W</td>
<td><img src="image1.png" alt="Diagram" /></td>
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<td><img src="image3.png" alt="Diagram" /></td>
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<tr>
<td></td>
<td>f=0.439</td>
<td>f=0.568</td>
<td>f=0.688</td>
</tr>
<tr>
<td>G + ΔT&lt;sub&gt;45K&lt;/sub&gt; + 1.5 W</td>
<td><img src="image4.png" alt="Diagram" /></td>
<td><img src="image5.png" alt="Diagram" /></td>
<td><img src="image6.png" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td>f=0.192</td>
<td>f=0.367</td>
<td>f=0.517</td>
</tr>
<tr>
<td>G + ΔT&lt;sub&gt;45K&lt;/sub&gt; + 2.3 W</td>
<td><img src="image7.png" alt="Diagram" /></td>
<td><img src="image8.png" alt="Diagram" /></td>
<td><img src="image9.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>
Layered model of reinforced concrete shell
• Nonlinear stress - strain relationship in compression

• Tension cracking

• Yielding of reinforcement

• Nonlinear concrete - steel bond

Nonlinear behavior of reinforced concrete including material damage
Sets of variables and iterations

\[
V := V + V = \mathbf{K}_T^{-1} \mathbf{P} = \mathbf{K}_T^{-1} (\mathbf{P} - \mathbf{F}_l) \quad P
\]

Structural level

\[
V, V^+ \quad V^+ = \mathbf{K}_T(V), \mathbf{F}_l(V)
\]

Finite element level

\[
 V^p, V^p_+ \quad k_T^p(V^p), f_T^p(V^p)
\]

Gauss-point level

\[
\mathbf{\varepsilon} = \{ \mathbf{\varepsilon}^{(\alpha \beta)} \} \quad \mathbf{\varepsilon}^+ = \{ \mathbf{\varepsilon}^{(\alpha \beta)}^+ \}
\]

or e.g.:

\[
\mathbf{\varepsilon} = \{ \mathbf{\varepsilon}^{\kappa} \mathbf{\varepsilon}^{\gamma} \} \quad \mathbf{\varepsilon}^+ = \{ \mathbf{\varepsilon}^{\kappa^+} \mathbf{\varepsilon}^{\gamma^+} \}
\]

Material point level

\[
\mathbf{\gamma}_{ij}, \mathbf{\gamma}_{ij}^+ \quad \mathbf{g}_1, \mathbf{g}_2
\]

\[
R_{ij}^m C_{mnkl}^+ \gamma_{kl}^+ = C_{ijkl}^+ \gamma_{ij}^+ = \mathbf{\sigma}_{ij}^+
\]

\[
\int_0^1 C_{mnkl} (\mathbf{\gamma}_{cp}) \ d\gamma_{kl} = \mathbf{\sigma}_{ij}
\]

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Statik und Dynamik
03-4-6
NDCT Niederaussem (ARHPC 85/35):
Crack patterns at D + 1.48 W; w > 0.00 mm
NDCT Niederaussem (ARHPC 85/35):
Crack patterns at D + 2.03 W; w > 0.00 mm
NDCT Niederaussem (ARHPC 85/35): Crack patterns at D + 2.51 W; w > 0.00 mm
G + $\Delta T_{45K}$ + $\lambda \ W$

Point A: $\theta = 0^\circ$, $z = 62.00 \text{ m}$

Point B: $\theta = 0^\circ$, $z = 142.00 \text{ m}$

Point C: $\theta = 0^\circ$, $z = 200.00 \text{ m}$

NDCT Niederaussem: (ARHPC 85/35)
Load - deformation curves at points A, B and C
NDCT Niederasseem: 30 - times exaggerated deformation at $G + \Delta T_{45K} + 2.30\ W$
\[ D_i = 1 - \frac{f_{i, \text{damaged}}}{f_{i, \text{undamaged}}} \]

NDCT Niederaussem: (ARHPC 85/35)
First 3 damage indicators for \( D + \lambda W \)
Damage indicators $D_i$:

$$D_i = 1 - \frac{f_{i, \text{damaged}}}{f_{i, \text{undamaged}}}$$

Graph showing:
- $D + \Delta T_{45K} + \lambda W$
- First 3 damage indicators $D_1, D_2, D_3$

NDCT Niederaussem: (ARHPC 85/35)
First 3 damage indicators for $D + \Delta T_{45K} + \lambda W$
Corrosion of NDCT

Outer face

Inner face (uncoated)
### Reduction of Dimensions and Stiffness

**Deterioration due to:**

<table>
<thead>
<tr>
<th></th>
<th>Concrete</th>
<th>Steel</th>
<th>Concrete</th>
<th>Steel</th>
<th>Concrete</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Carbonation</td>
<td></td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>2. Chloride penetration</td>
<td></td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td>○</td>
</tr>
<tr>
<td>3. Sulfate attack</td>
<td></td>
<td>●</td>
<td>●</td>
<td></td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>4. Abrasion, erosion</td>
<td></td>
<td>●</td>
<td></td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Freeze-thaw-cycles</td>
<td></td>
<td></td>
<td>●</td>
<td></td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>6. Fire: permanent, during fire</td>
<td></td>
<td>○</td>
<td>●</td>
<td></td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

---

**Mechanistic empirical deterioration models for RC members**
\[ D_i = 1 - \frac{f_{i, \text{damaged}}}{f_{i, \text{undamaged}}} \]

NDCT Goesgen: First 3 damage indicators: \( G + \Delta T_{45K} + \Delta T_{\text{hygr}} + \lambda W \)
Load combination:
Ultimate monotonic load factor $\lambda_{\text{crit}}$: $D + \lambda W$  $D + \Delta T_{45K} + \lambda W$

$1.71$  $1.68$

Wind load histories:

$t = 0$: One initial gale

$\lambda_{\text{init}} = 1.20$  $\lambda_{\text{init}} = 0.95$

$t = 10 \cdot 20 \cdot 30 \cdot 40$ years:

one further gale of $\lambda = 1.00$

Corrosion histories:

After a bar is reached by a crack, reinforcement corrosion starts with corrosion rate of $1\% / a$ of bar diameter: At $t = 0$

concrete corrosion of $0.6$ mm/a is activated on inner face.

Life-time simulations
Life-time simulations

\[ D + \Delta T_{45K} + \lambda W \]

Wind load factor \( \lambda \)

Maximum shell displacement [m]

- Life-time \( t_0 + 0 \) years
- Life-time \( t_0 + 10 \) years
- Life-time \( t_0 + 20 \) years
- Life-time \( t_0 + 30 \) years
- Life-time \( t_0 + 40 \) years
Life-time simulations

- Life-time $t_o + 0$ years
- Life-time $t_o + 10$ years
- Life-time $t_o + 20$ years
- Life-time $t_o + 30$ years
- Life-time $t_o + 40$ years

Wind load factor $\lambda$

Maximum shell displacement [m]
NDCT RWE Lignite Power Plant Neurath 2007
Thermal power plant with cleaned flue gas injection
Dry cooling tower - Project

Niederassem

Trojan Nuclear Plant - USA 1971; 162.00 m

Mülheim-Kärlich - D 1977; 162.00 m

Stiffening rings

Heat exchanger

Hams Hall - GB 1931; 68.00 m

Heerlen - NL 1914; 35.00 m

25.00 m

Valenciennes - F 1904

Development of natural draft cooling towers
Large shell structures for power generation technologies

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   Construction principles • loading and internal stress variables • shape optimization • instability and vibrations • damage and life-duration

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   Construction principles • shell strength versus ring stiffening • instability and vibrations

4. Conclusions
Small solar tower of 500m of height
Meridional ($n_{22w}$) and in-plane shear ($n_{12w}$) forces, 500m tower
Instability modes: 500m tower without stiffenings rings (G+W+S)

1\textsuperscript{st} instability mode: $\lambda_1 = 4.77$

2\textsuperscript{nd} instability mode: $\lambda_2 = 4.86$

3\textsuperscript{rd} instability mode: $\lambda_3 = 6.58$
Instability modes for 500m tower with 4 stiffenings rings (G+W+S)

1\textsuperscript{st} instability
mode: $\lambda_1 = 8.25$

2\textsuperscript{nd} instability
mode: $\lambda_2 = 8.50$

3\textsuperscript{rd} instability
mode: $\lambda_3 = 10.35$
Artist’s view of large solar chimney power plant

Acc. Stinnes (GreenTower Ltd.): Short Executive Summary June 2007
From high natural draft cooling towers to solar chimneys

818 m Burj Dubai

200 m NDCT Niederaussem

500 m solar chimney

120.00m

120.00m

136.00

136.00

250.00m

250.00m

500.00m

500.00m

750.00m

750.00m

1500 m solar chimney

[400 MW]

170.00

1500.00m

1000 m solar chimney

[200 MW]

145.00

1000.00m

350.00m

350.00m

130.00m

130.00m

120.00m

120.00m
Results: Power output
Regulating plant power output according to demand (cont.)

- Plastic covered water tanks
  - Provide more uniform daily power output profile (static control)
  - Relatively shallow tanks
  - Covered with transparent plastic (no water evaporation)
  - Black inside bottom
  - Insulated outside bottom and sides (no heat losses to environment)

Regulating plant power output according to demand (cont.)

- Plastic covered water tanks
  - Partially covered collector area, constant tank depth
  - Significant static control
  - 2.4% (1/2 Area), 2.7% (3/4 Area), 2.6% (Full Area) reduction in annual power output
Regulating plant power output according to demand (cont.)

- Dynamic control
  - Base or peak power generation facility
  - Inclusion of additional collector roof
  - Inclusion of airflow regulating mechanisms
  - Plant given ability to store or release energy when needed

Base load strategy
- Keep power as constant as possible

Peak load strategy
- Maximum power delivered between 07:00 and 12:00 and 17:00 and 22:00 (Eskom)

Regulating plant power output according to demand (cont.)

- Double glazed secondary collector roof
  - Base load: excellent control
  - 7.9% increase in annual power output
Regulating plant power output according to demand (cont.)

- Secondary collector roof
  - Peak load: good control
  - 2% increase in annual power output

Gust Wind Profile

- Gust speed in m/s
- Height over ground in m

- 200m Niederaußem
- 300m Eiffelturm
- 800m Burj Dubai
- 1500m Green Tower
NDCT Niederassem: Types of circumferential wind pressure distribution $c(\Theta^1)$

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Statik und Dynamik
03-4-5
Green Tower Project Namibia

Solar Chimney

32 Turbine openings Ø 31 m

Collector roof

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GreenTower Project Namibia: Tower foot alternative

32 Additional Stiffening Walls d = 2.0m

32 Turbines Ø 31 m
1000m tower for a 200MW SCPP

View

Cross-section

Stiffening rings

Wall thickness

Collector roof

16 Turbines $\varnothing$ 32.00m

R = 3000 m

0.25

0.25

0.35

0.45

0.65

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Solar Chimney Project Arabia: 1000m variant

- Chimney wall
- In-situ concrete
- Welded steel box filled with RC
- Welded hollow sections square 300 x 8
- Welded end plates

Tower geometry
- Ø 145.60 m
- Ø 133.40 m
- Ø 260.60 m
- Top view on tower

Stiffening rings
- Ø 122.72 m
- Ø 119.17 m
- Ø 111.05 m

Upper chimney edge with edge beam
- Wall thickness
- View on turbine openings

Spoke wheel stiffening ring beam
(carbon fiber strings)

16 Turbine openings
- 12.00
- 2.50
- 0.05

Solar Chimney 1000 m

K & P 08/3-43
Krätzig & Partner Ingenieurgesellschaft für Bautechnik mbH
Instability modes of 1000m tower for G+W+S

1\textsuperscript{st} instability
mode: $\lambda_1 = 5.32$

2\textsuperscript{nd} instability
mode: $\lambda_2 = 5.91$

3\textsuperscript{rd} instability
mode: $\lambda_3 = 7.82$
Vibration modes of 1000m tower

1st vibration mode: $f_1 = 0.17$ Hz

2nd vibration mode: $f_2 = 0.21$ Hz

3rd vibration mode: $f_3 = 0.39$ Hz
Vibration modes 1, 2 and 3 of 750m tower

1\textsuperscript{st} vibration mode $f_1 = 0.17$ Hz

2\textsuperscript{nd} vibration mode $f_2 = 0.34$ Hz

3\textsuperscript{rd} vibration mode $f_3 = 0.50$ Hz
Vibration modes 4, 5 and 6 of 750m tower

4th vibration mode $f_4 = 0.77$ Hz

5th vibration mode $f_5 = 0.77$ Hz

6th vibration mode $f_6 = 0.84$ Hz
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4. Conclusions: When will SUPCs be improved structures like NDCTs?