Wilfried B. Krätzig, Reinhard Harte, Ralf Wörmann:

Large shell structures for power generation technologies

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4. **Conclusions**

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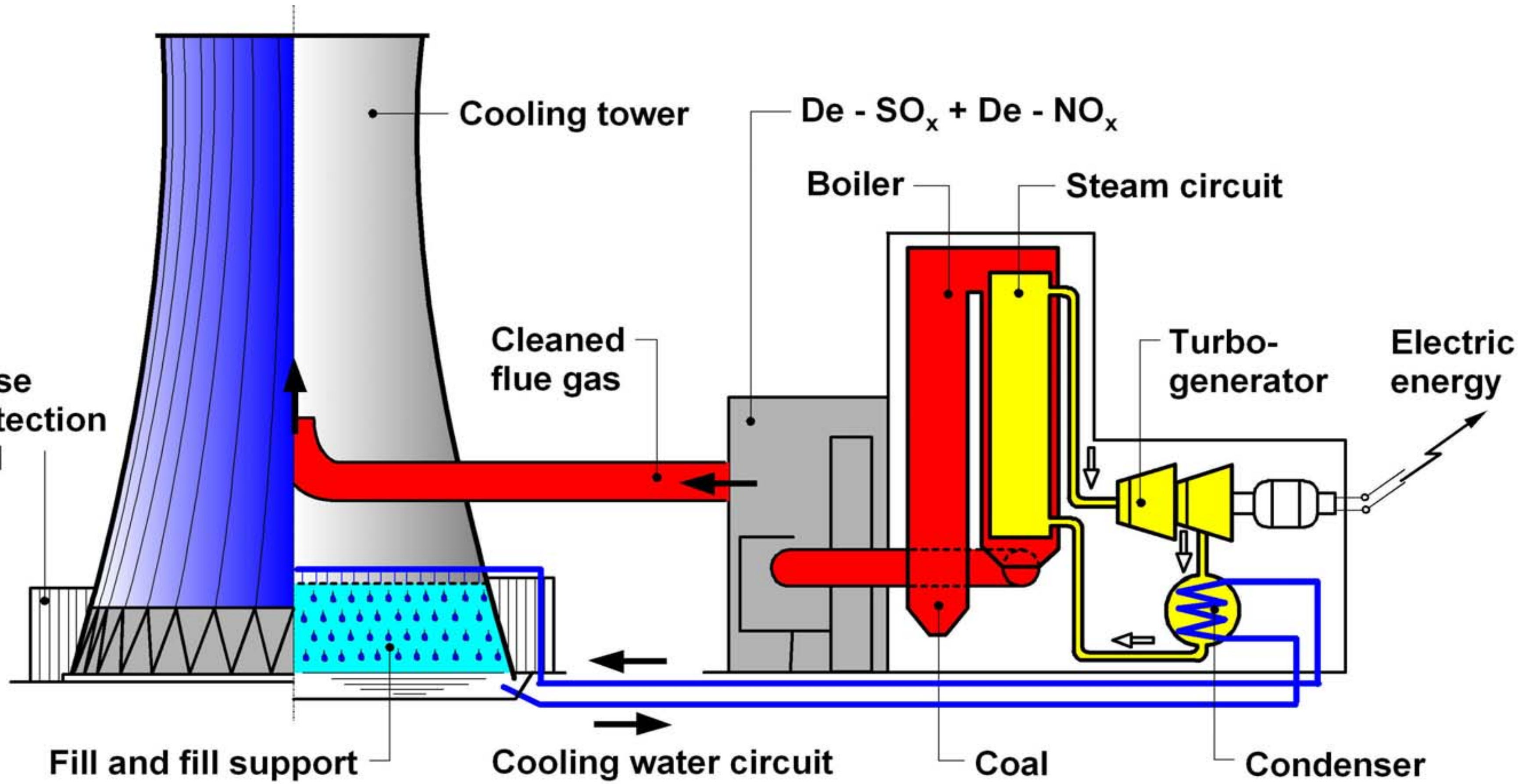
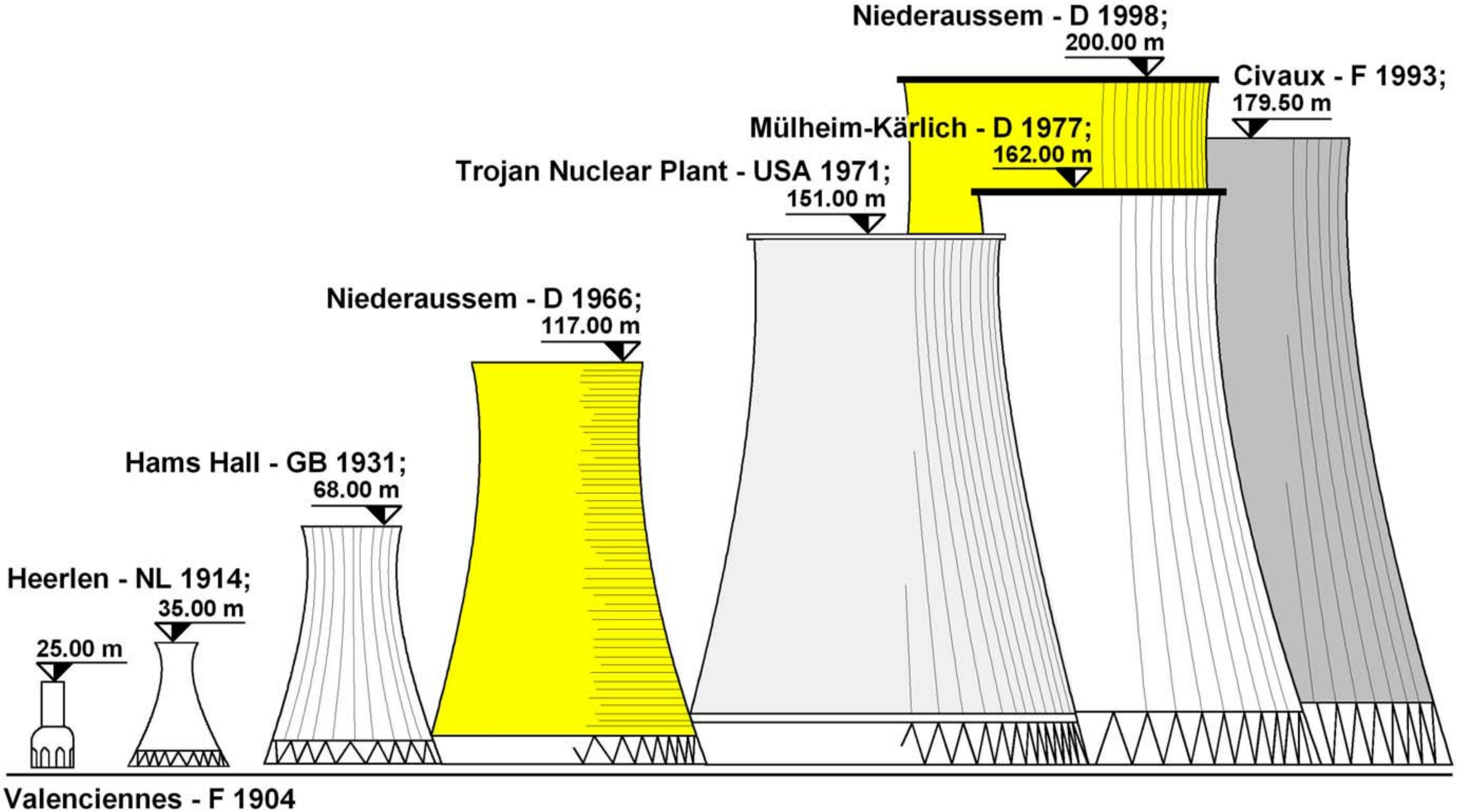
05 - 1-1
Ruhr - Universität Bochum * Statik und Dynamik

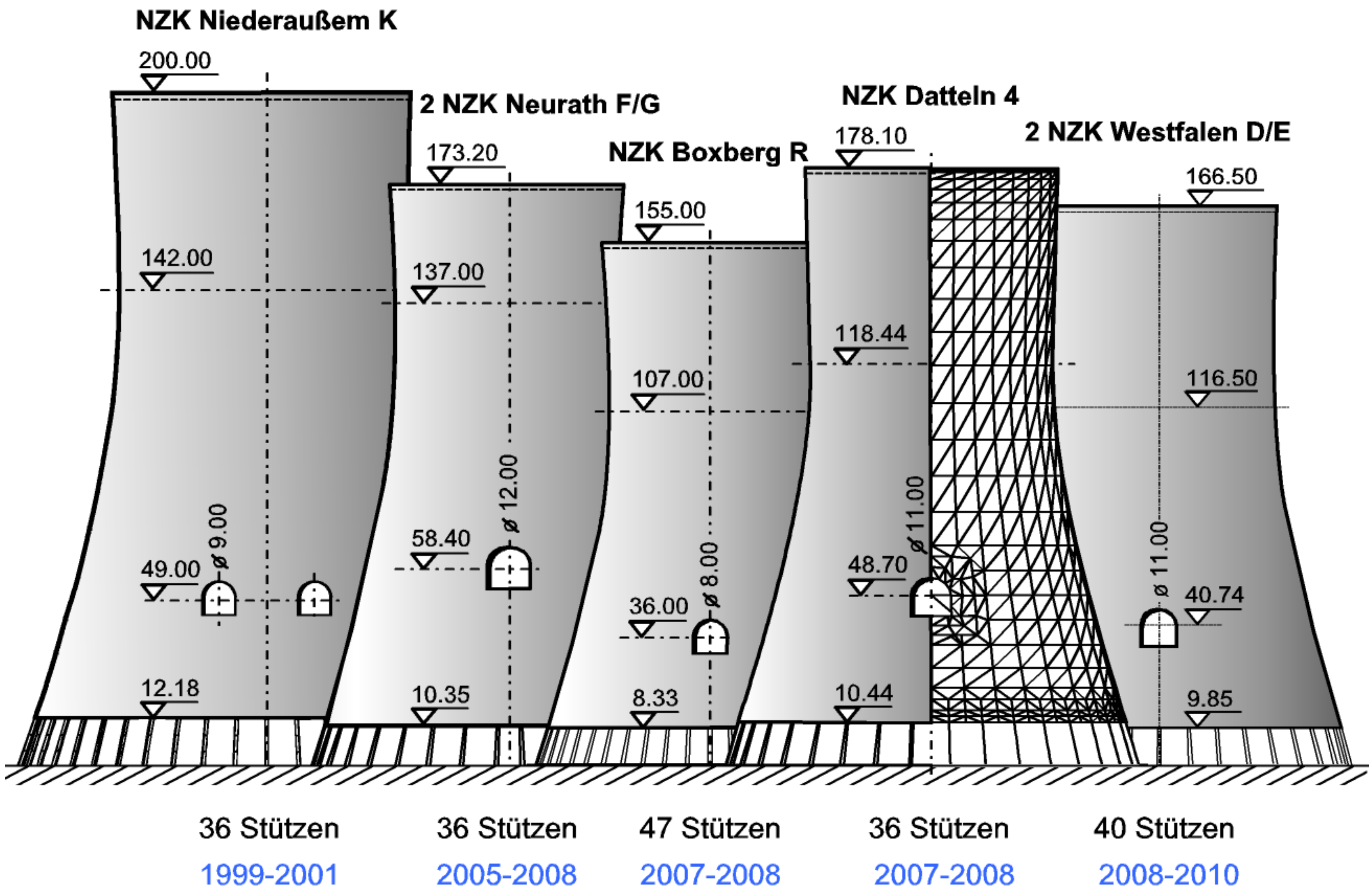


Thermal power plant with cleaned flue gas injection

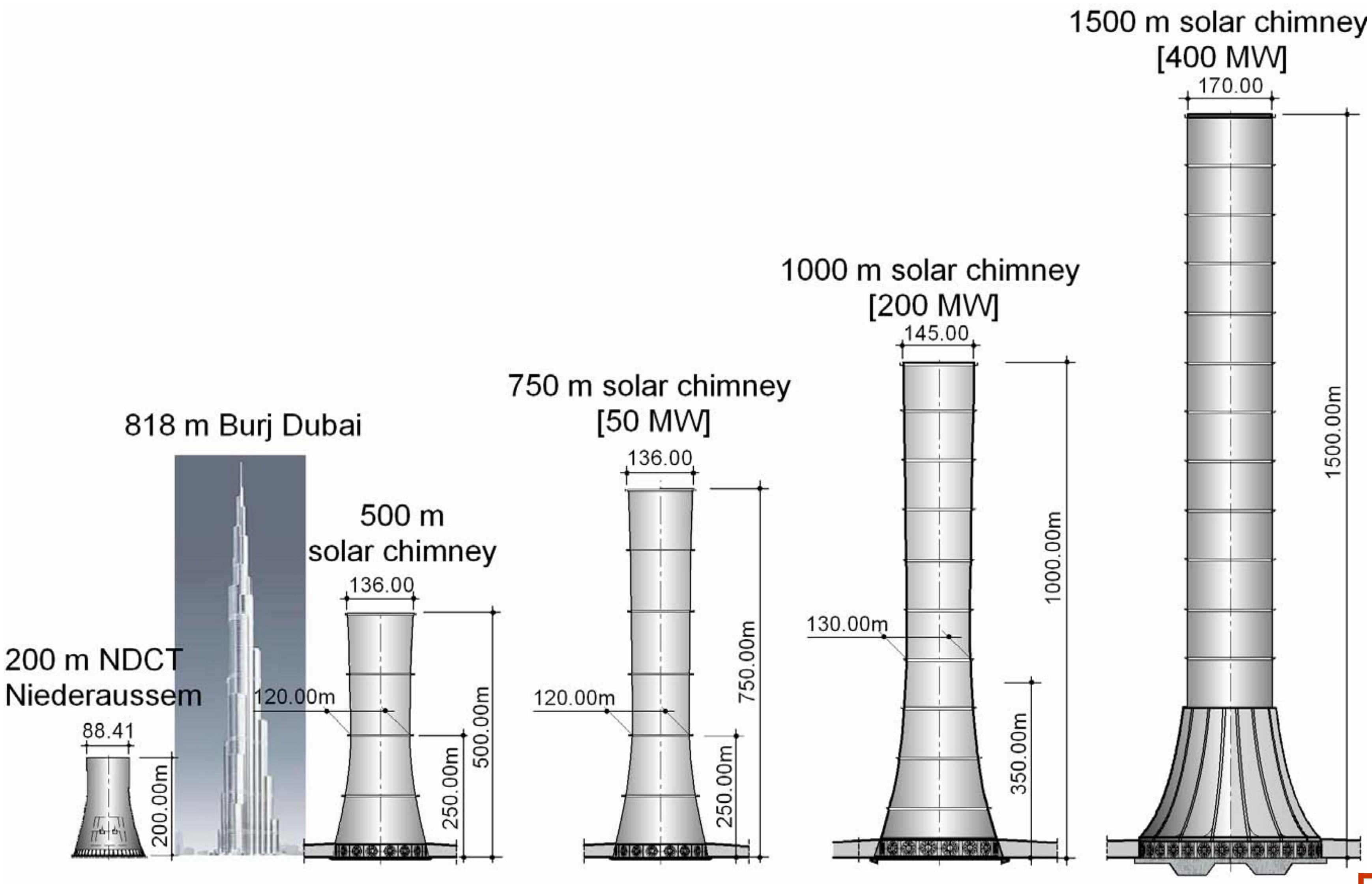


Development of natural draft cooling towers

Actual cooling tower projects made of high-performance concrete in Germany



From natural draft cooling towers to solar chimneys



Solar GreenTower ® Competence Network

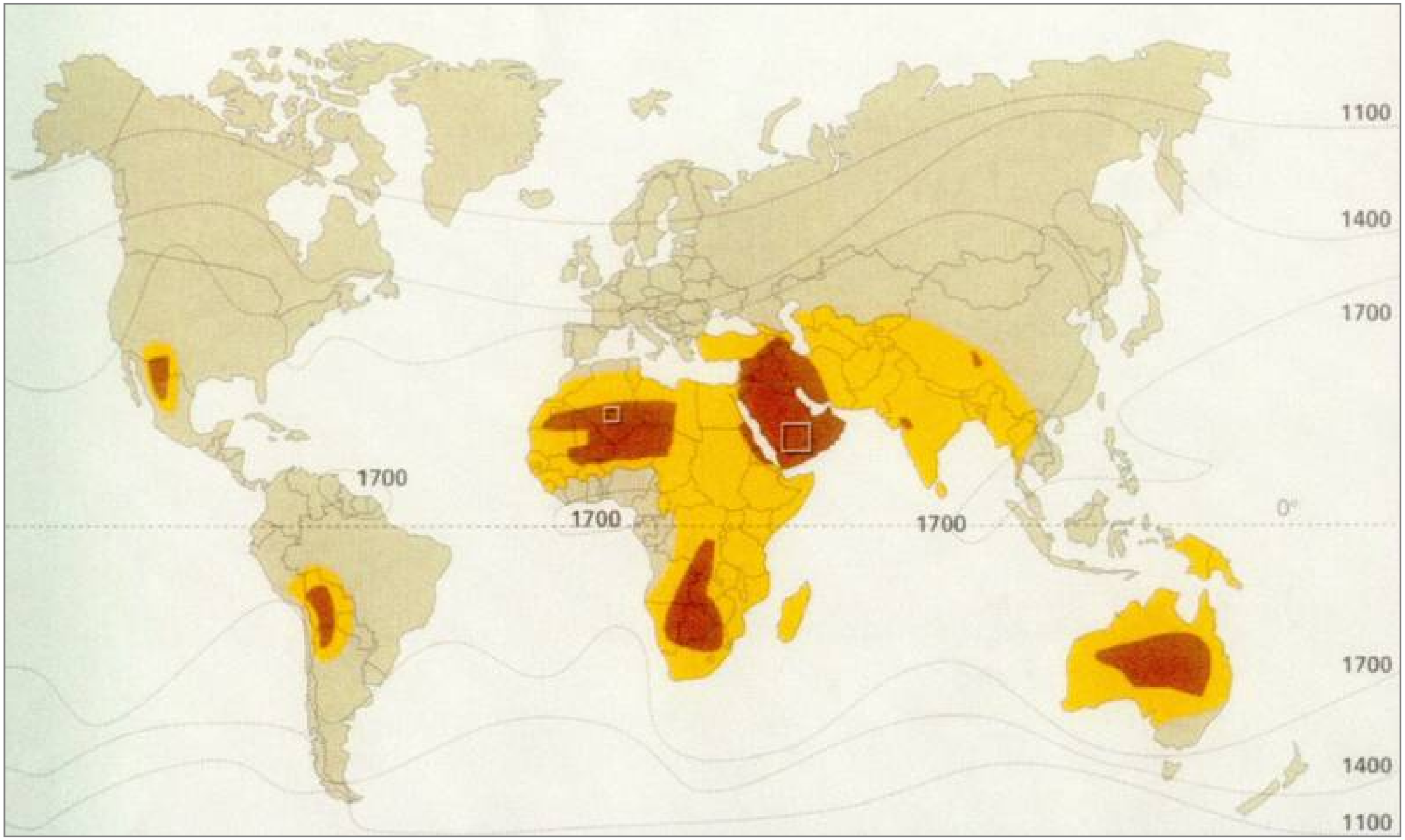
- **W.W. Stinnes** M.Sc.(Phys.), Haiger (Germany) und Pretoria (RSA)
- **Prof. Dr. R. Harte,** U. Wuppertal + Krätzig & Partner, Bochum
- **Prof. Dr. Dr. E.h. W.B. Krätzig,** Ruhr-University + Krätzig & Partner, Bochum
- **Prof. Dr. H.- J. Niemann,** Ruhr-Universität und Niemann & Partner, Bochum
- **Prof. 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

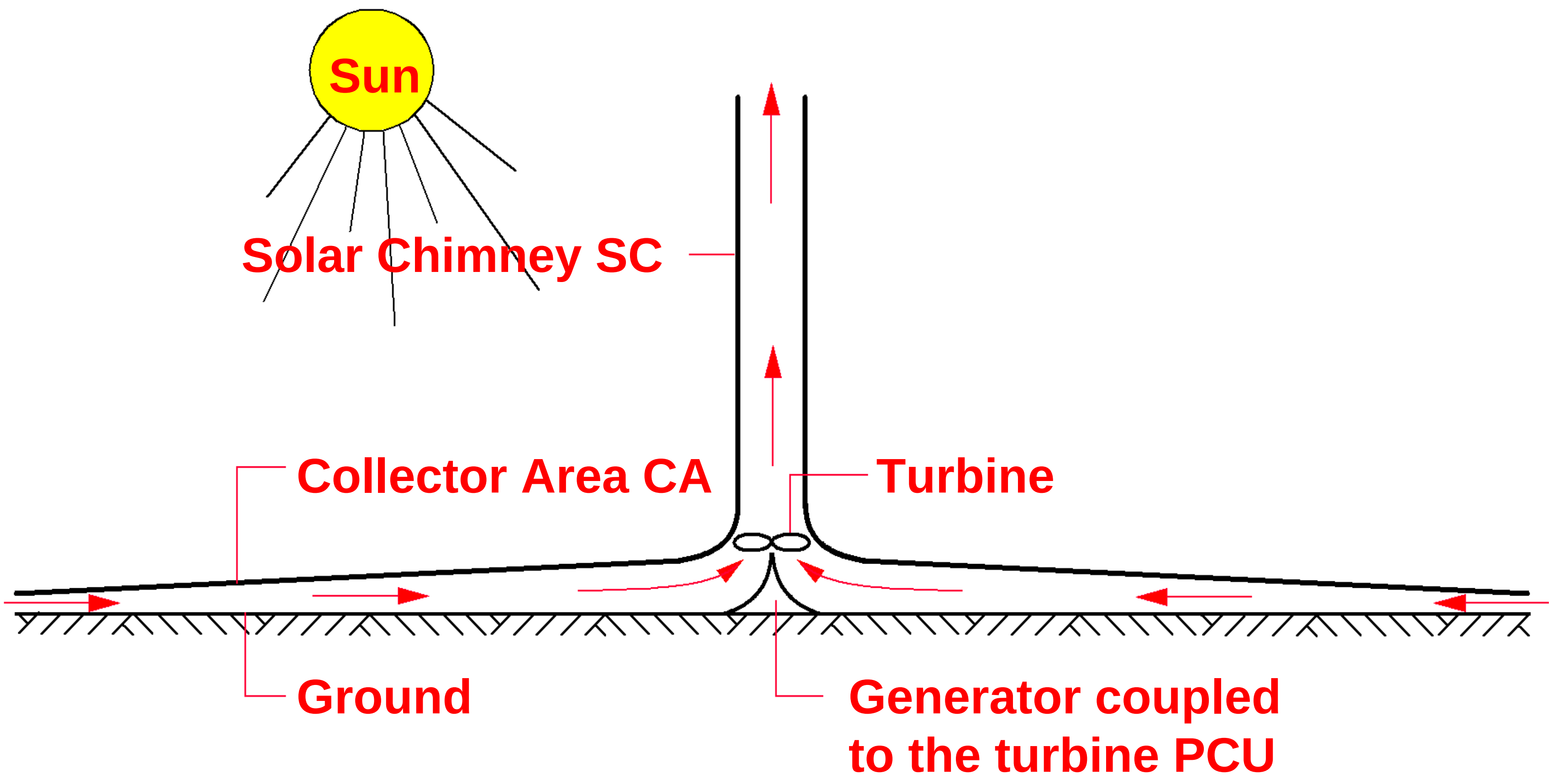
Annual global solar radiation (kWh / m²)

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



Acc. Kroeger/Praetorius (Univ. Stellenbosch): Solar Chimney Power Plant Performance

Schematic solar chimney power plant



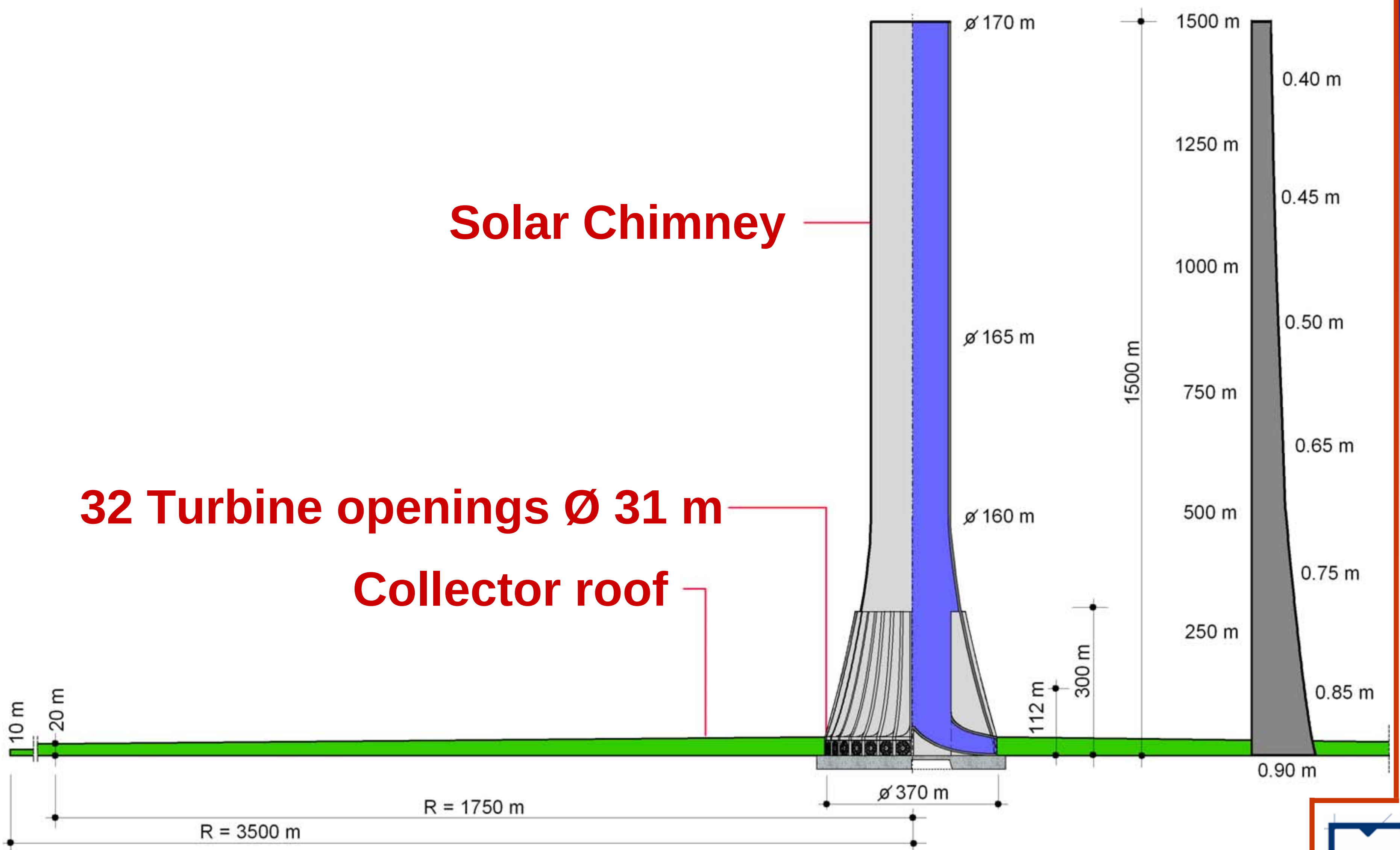
Acc. Kroeger/Praetorius (Univ. Stellenbosch):
Solar Chimney Power Plant Performance

Prototype solar chimney power plant

Manzanares, Spain (1982), prototype project Prof. J. Schlaich

Acc. Kroeger/Praetorius (Univ. Stellenbosch):
Solar Chimney Power Plant Performance

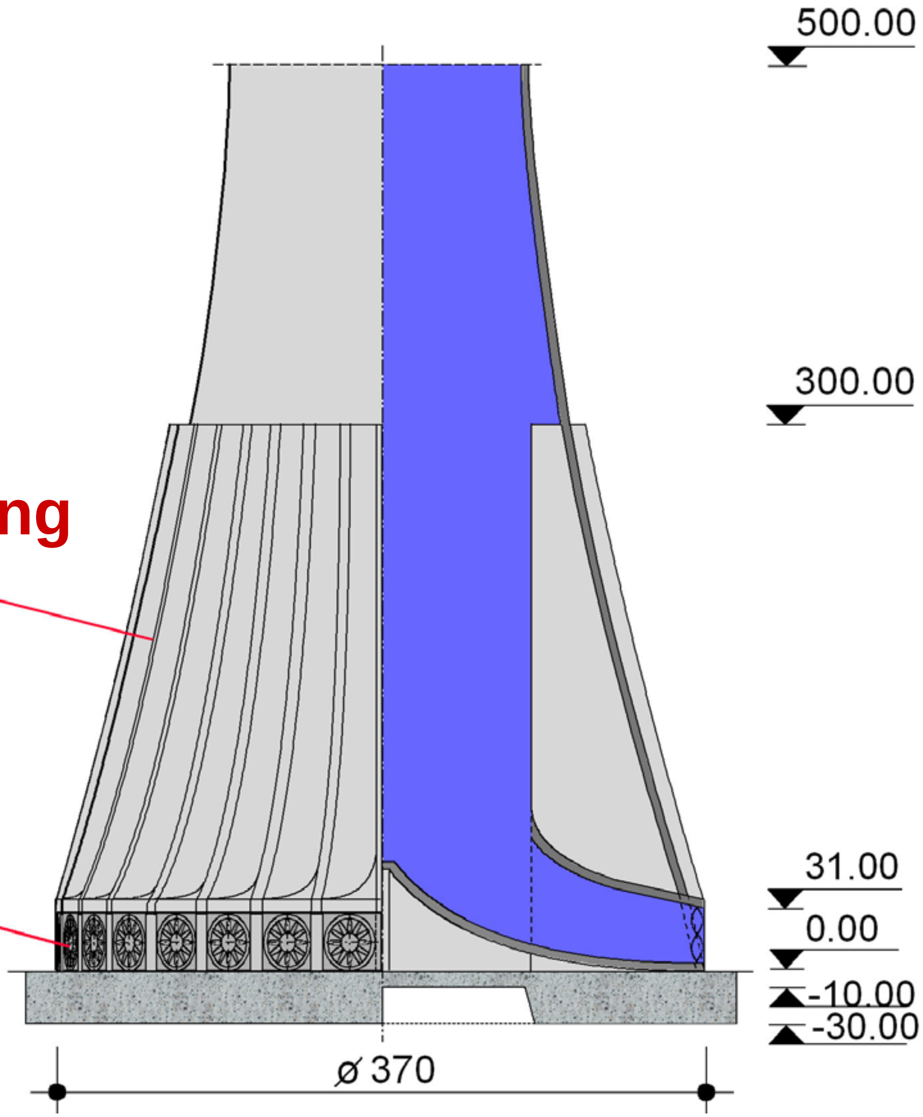
Natural Hazard Resistant Design of the Green Tower



GreenTower Project Namibia: Tower foot alternative

32 Additional Stiffening Walls d = 2.0m

32 Turbines Ø 31 m



Artist's view of large solar chimney power plant

Acc. Stinnes (GreenTower Ltd.):
Short Executive Summary June 2007

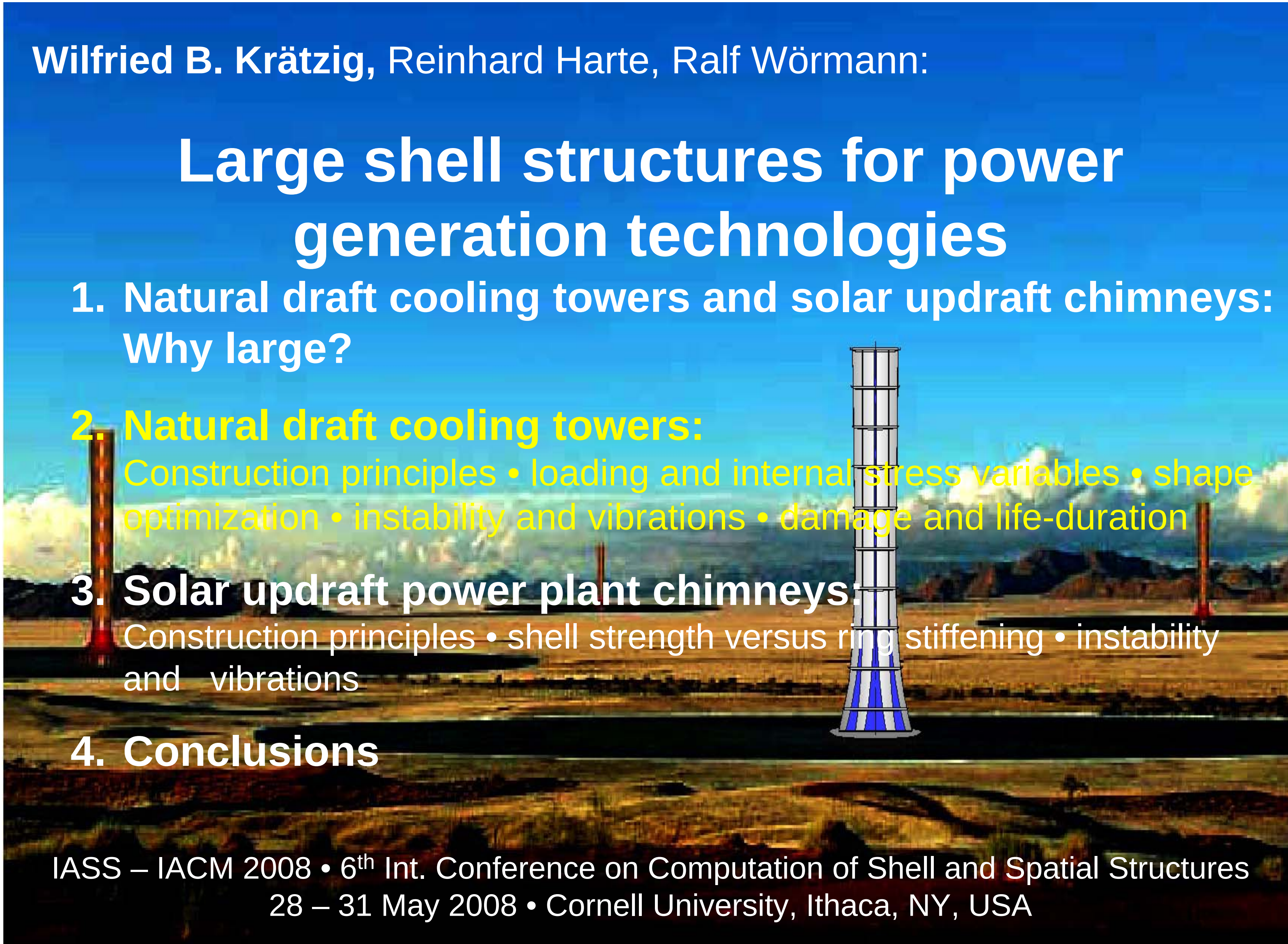


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Foto 14

NDCT RWE Lignite Power Plant Neurath 2007


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Foto 24


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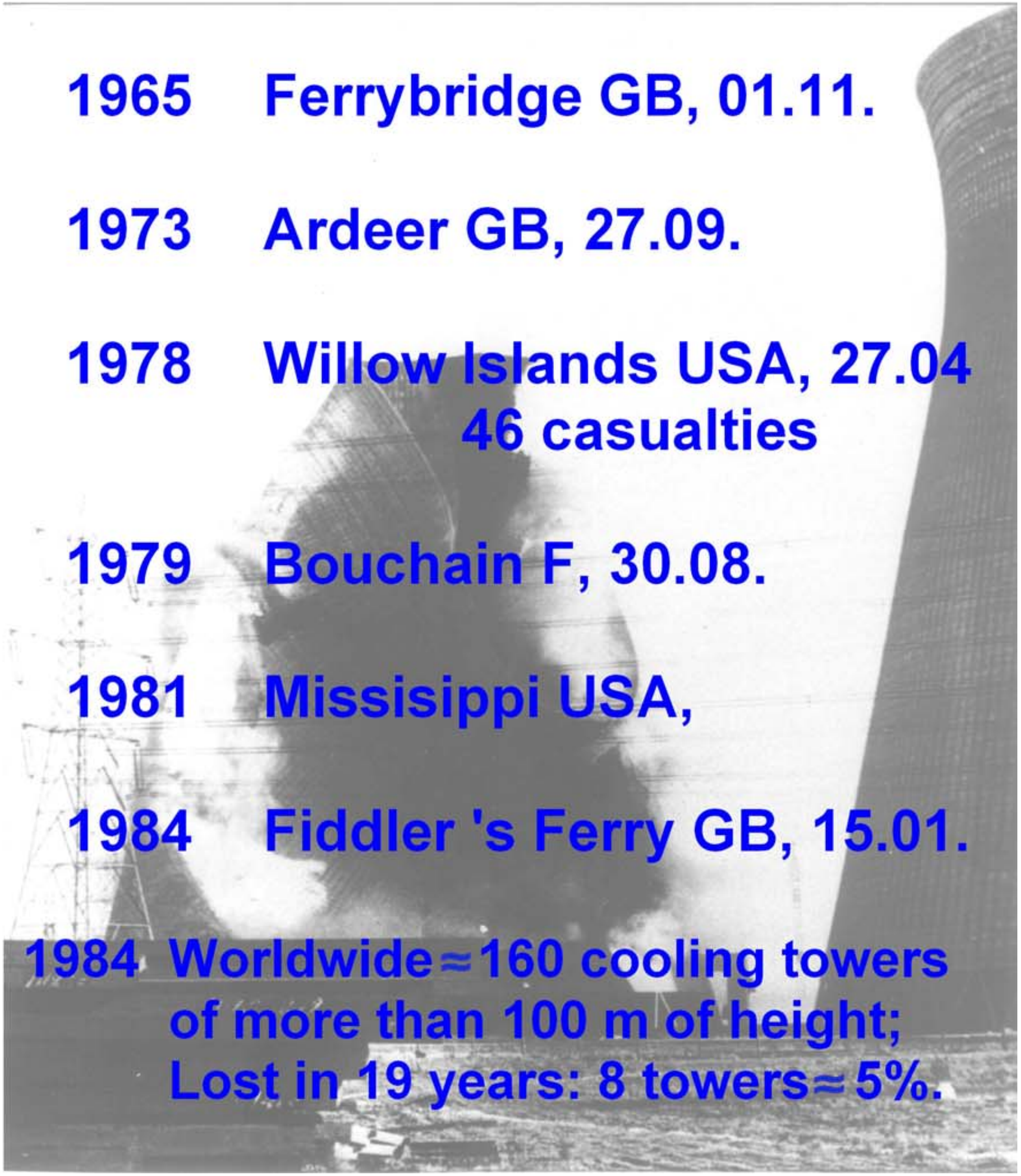
Ingenieurgesellschaft für Bautechnik mbH
Foto2

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.

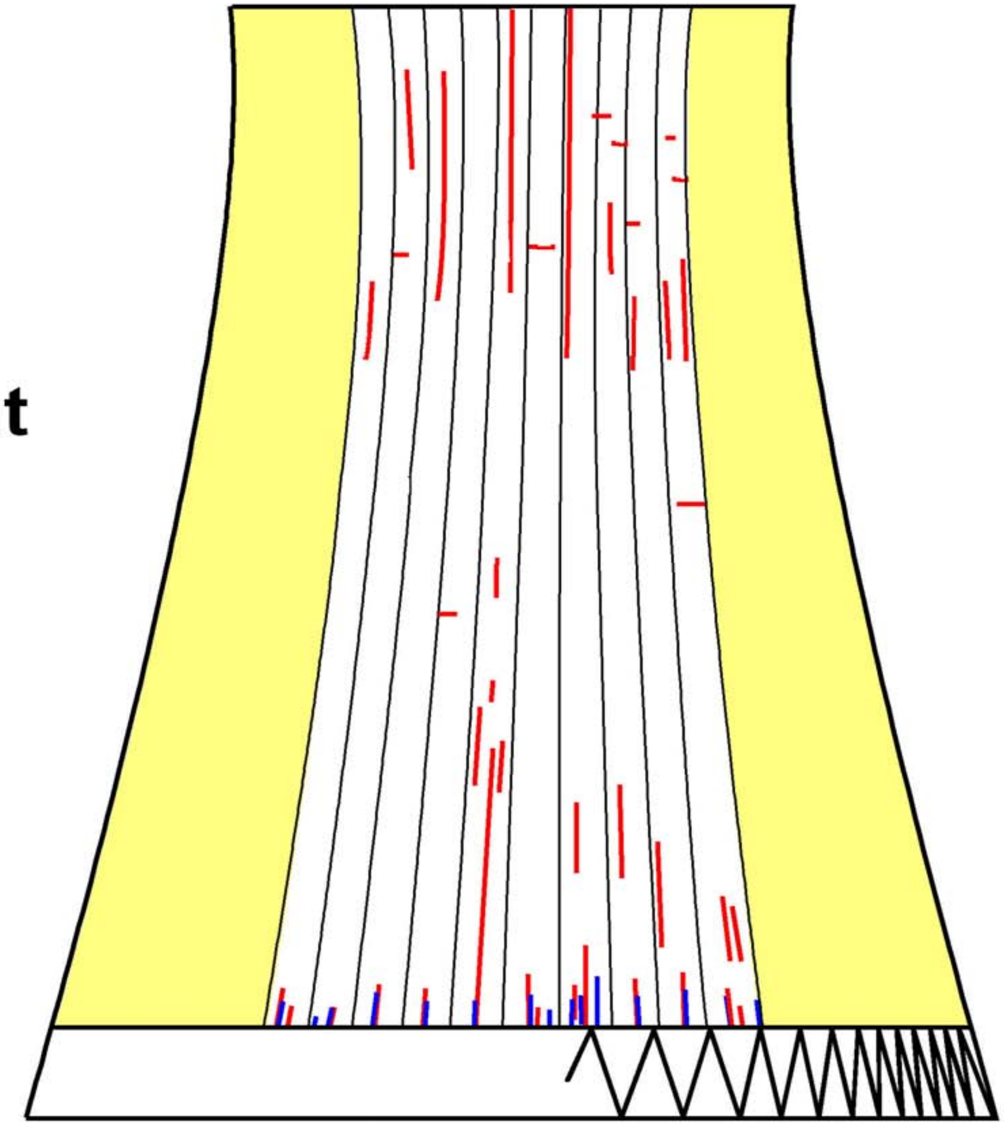
1981 Missisippi USA,

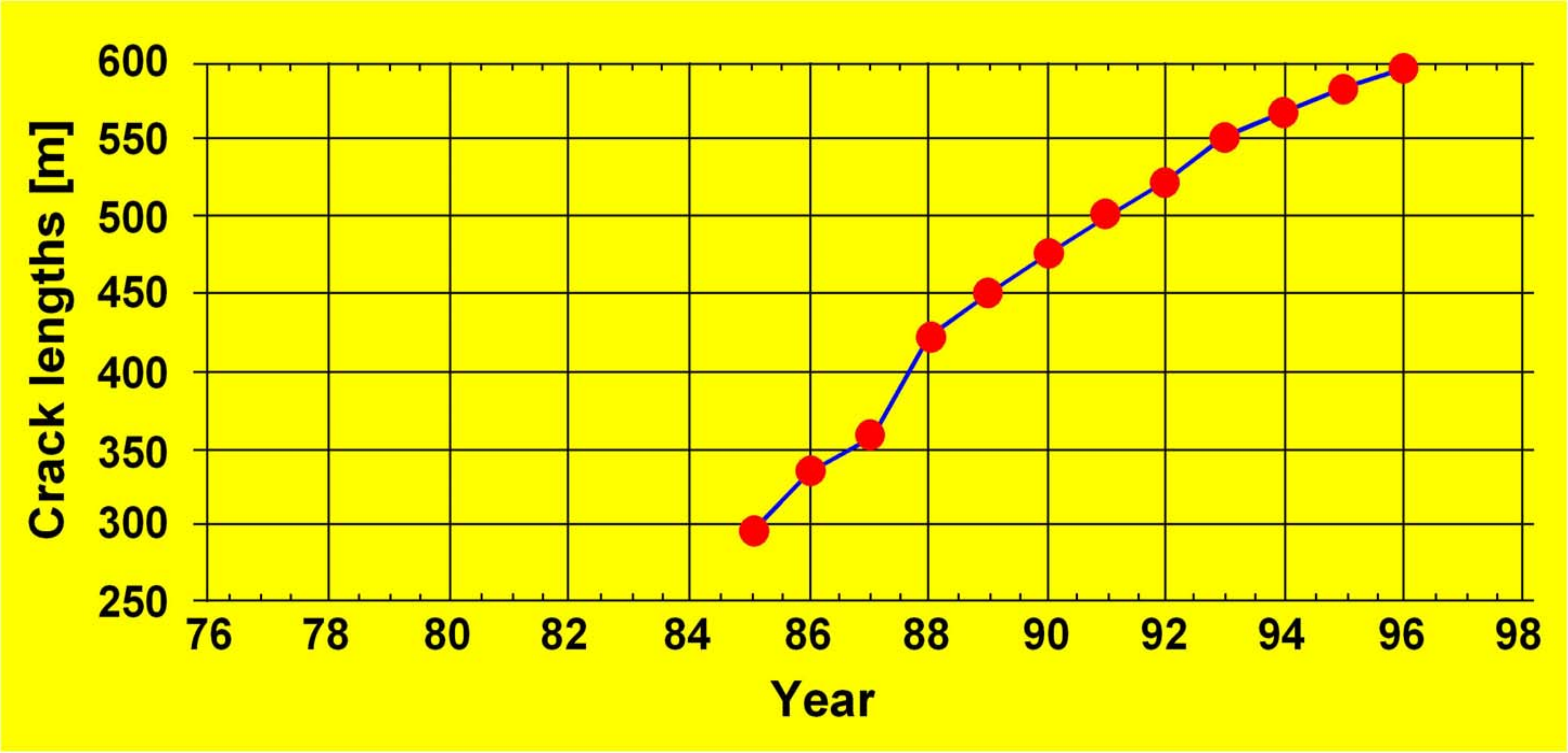
1984 Fiddler 's Ferry GB, 15.01.

1984 Worldwide ≈ 160 cooling towers of more than 100 m of height;
Lost in 19 years: 8 towers ≈ 5%.

NDCT Goesgen: Aerial view

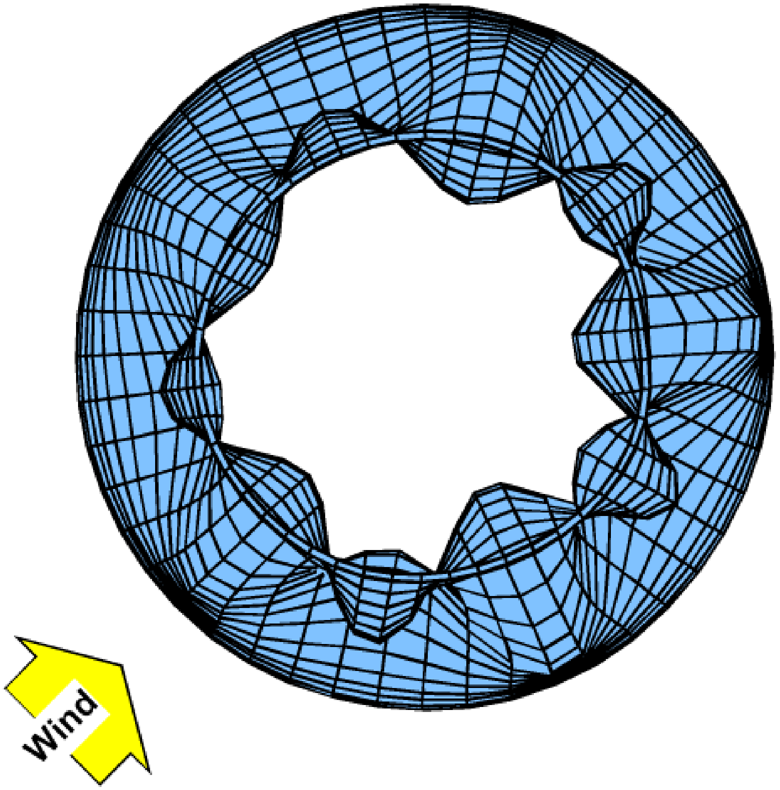
Monitored cracks of a cooling tower segment



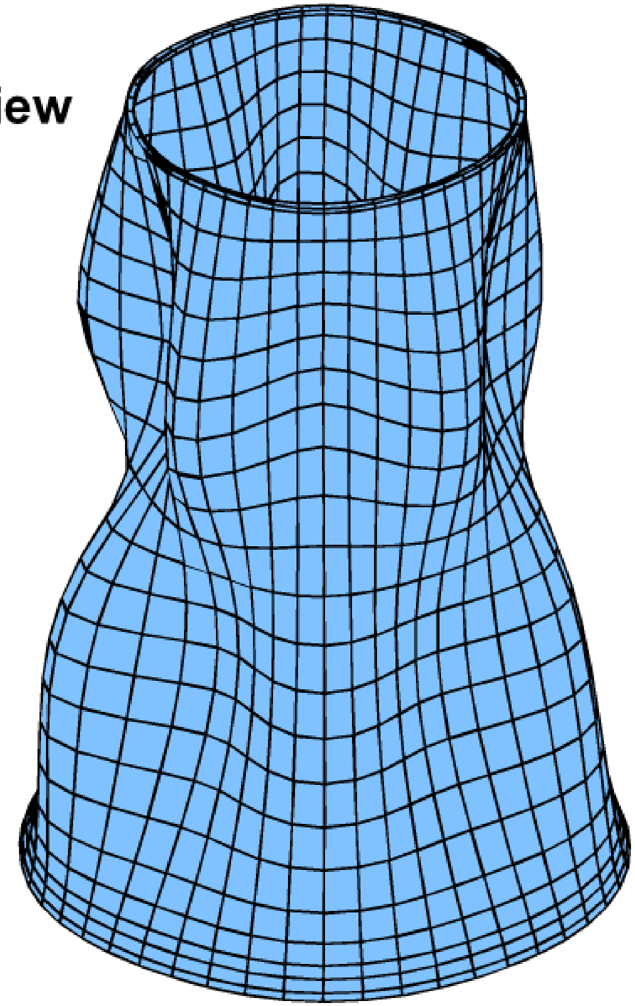


Crack growth:
Accumulated lengths of monitored cracks

Top View

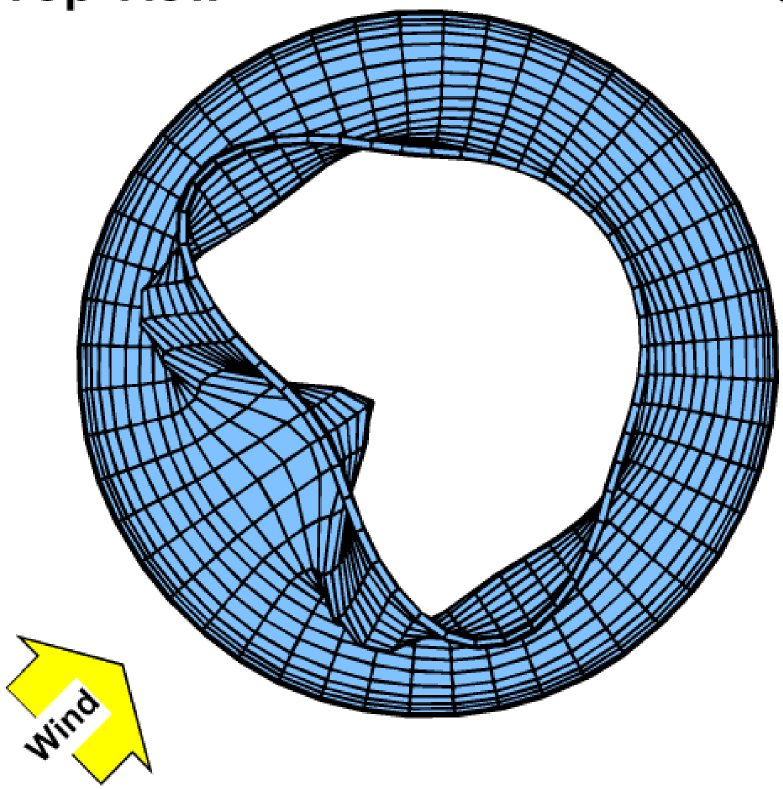


Side View

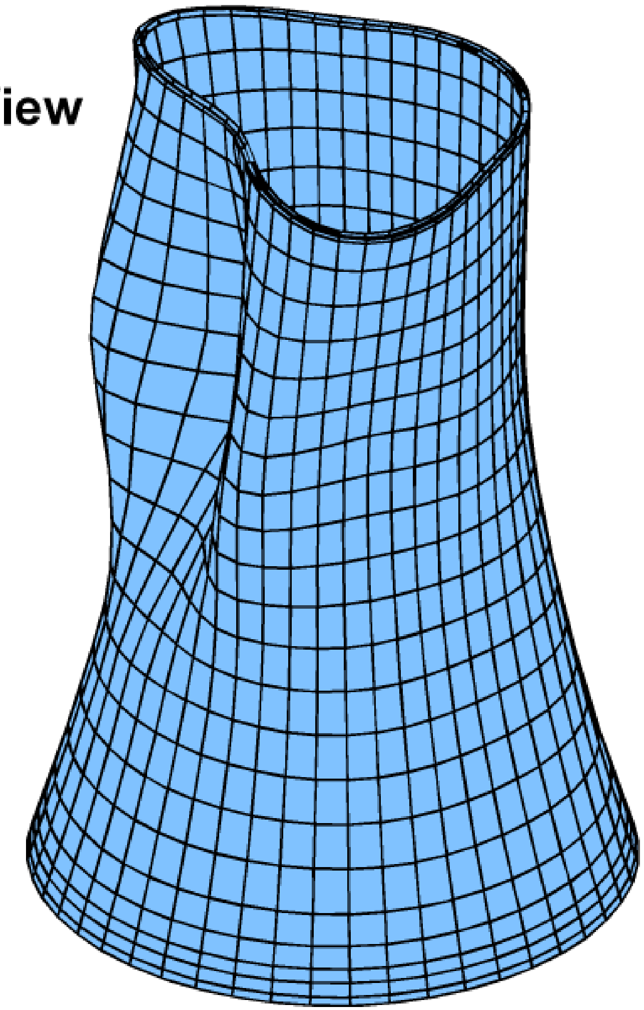


Pre-design NDCT Niederaussem:
First eigenmode of virgin tower

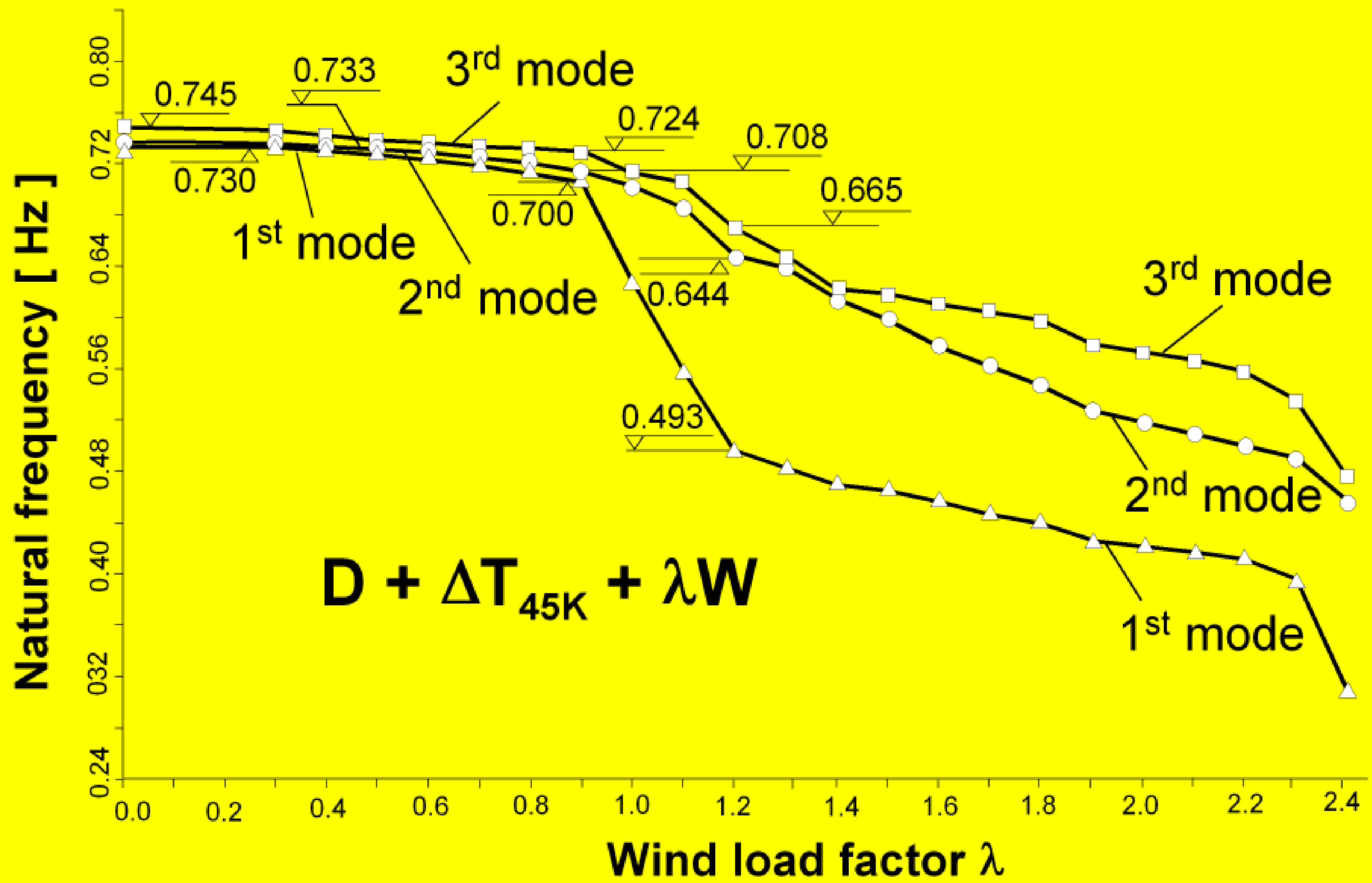
Top View



Side View

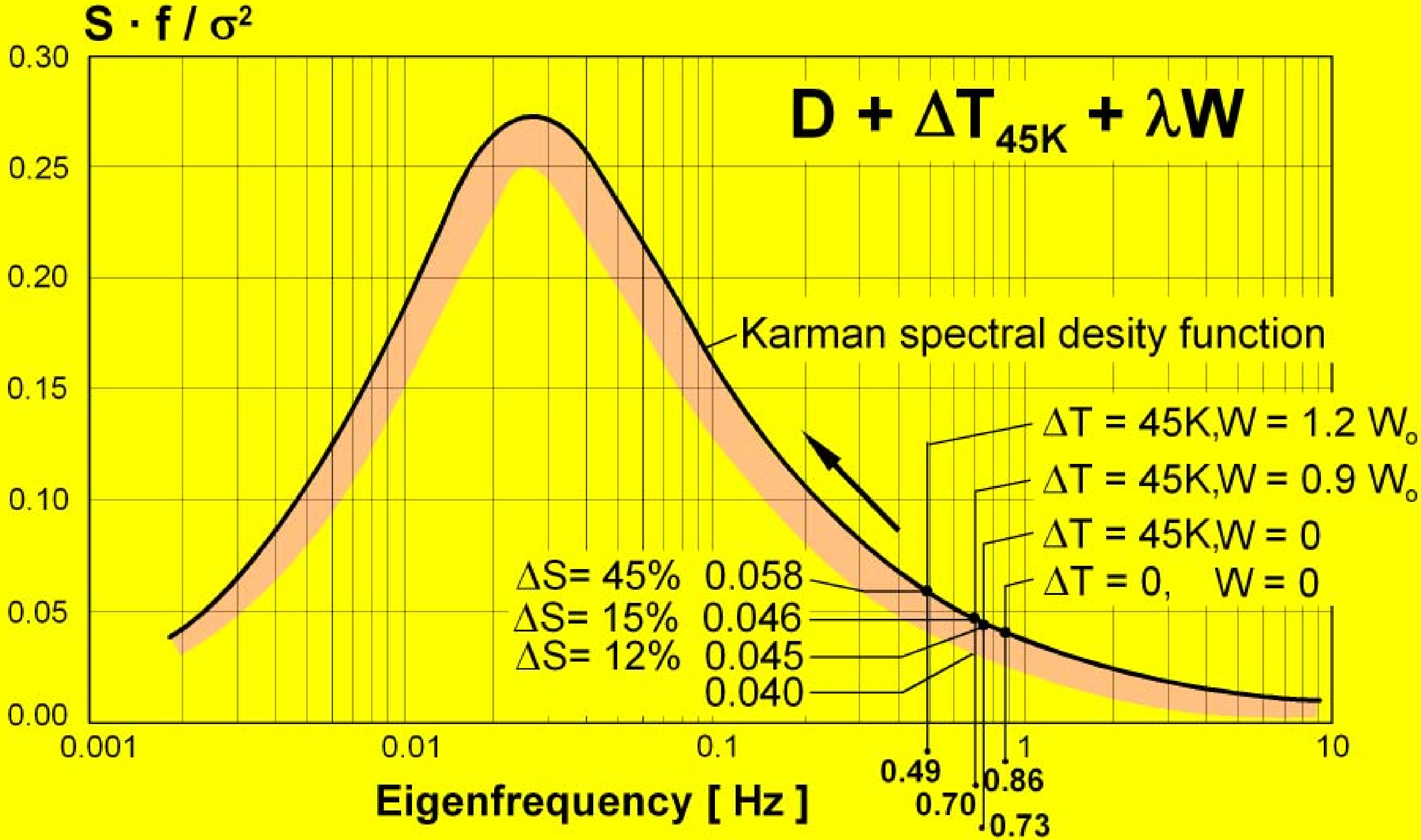


Pre-design NDCT Niederaussem:
First eigenmode at D + 1.4W



Wind load factor versus natural frequencies

Plane and open ground, WZ II Germany: v_m= 40.0 m/s, z = 100.0 m, L_{ux}=225.0 m



Increase of Wind-Dynamics due to Cracking

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:
Computervision of
new power station
with existing blocks
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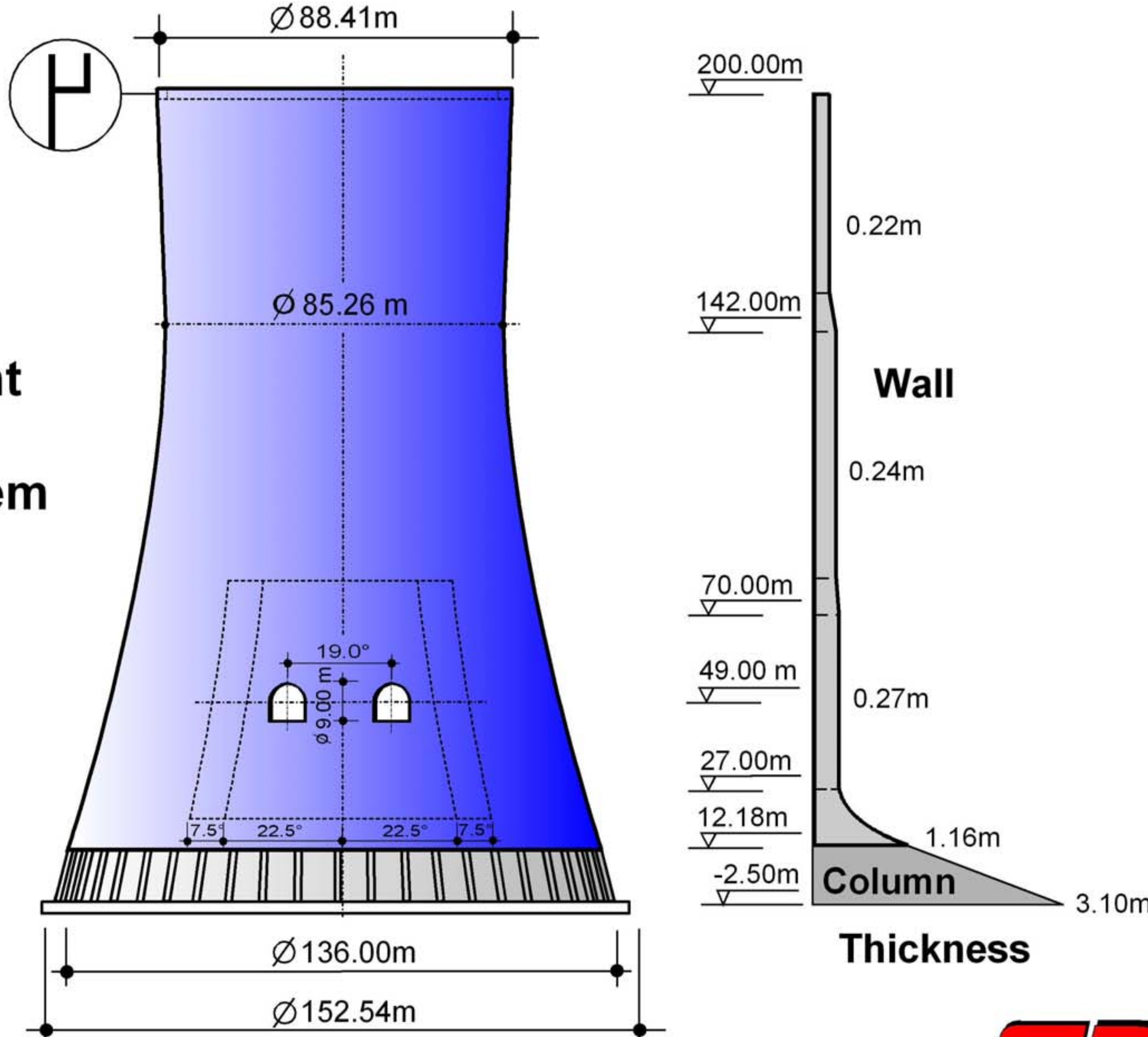
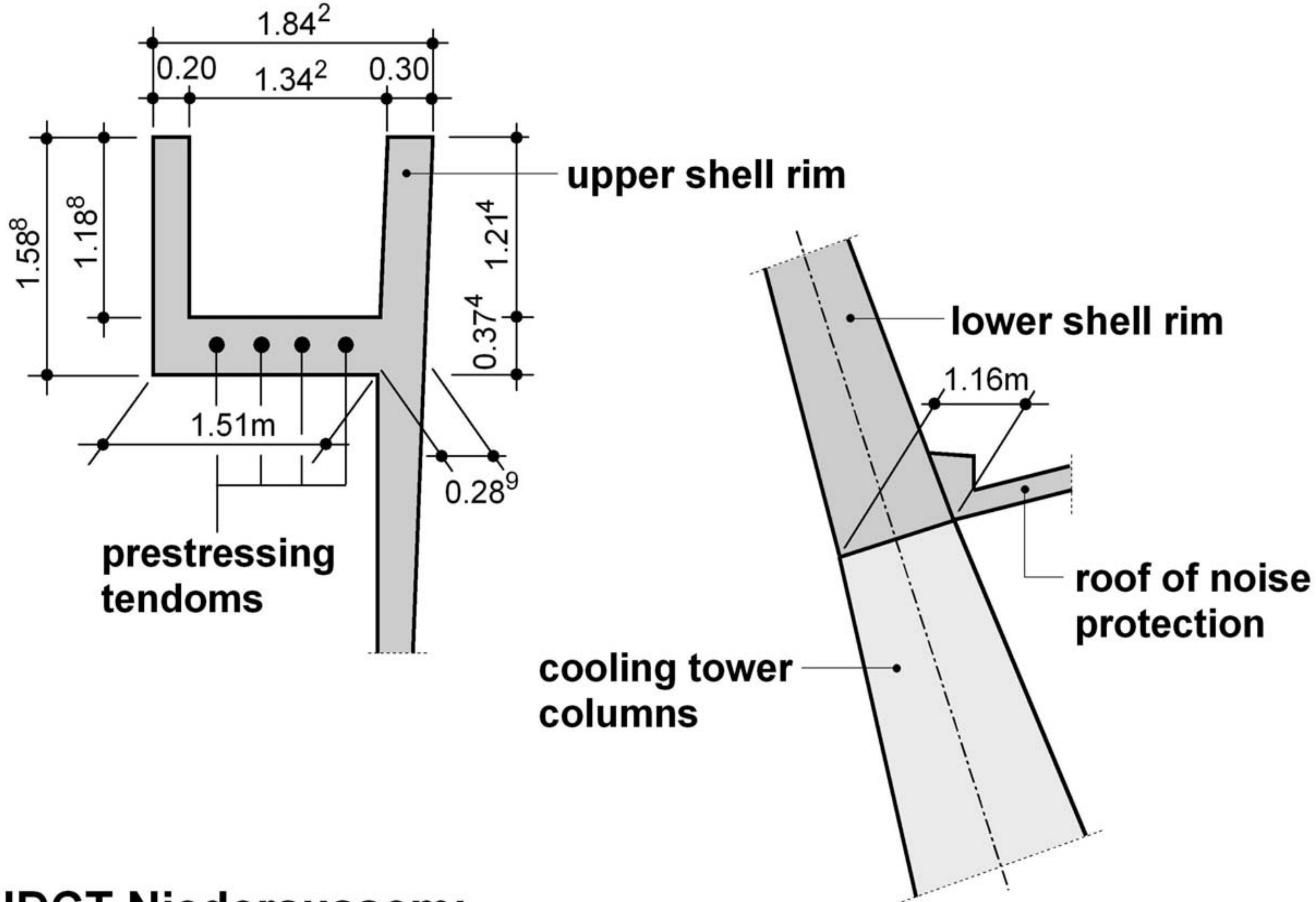
Natural draught cooling tower at Niederaussem Power Station (Execution)





NDCT Niederaussem: Geometry of both edge members

Shell

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

Geometry

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

α = 72.0°
H_o = 12.18 m
H_u = - 2.50 m
$W_o \cdot D = 1.16 \cdot 1.40$ m
$W_u \cdot D = 3.10 \cdot 1.40$ m

Material

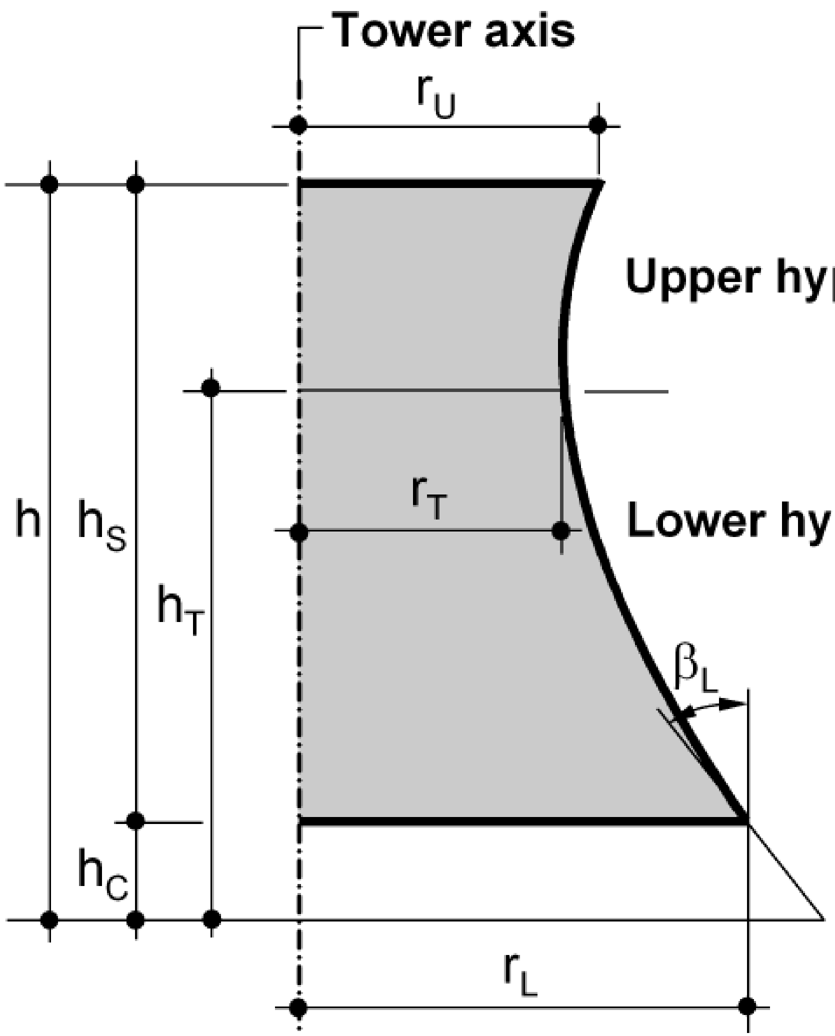
Steel: BSt 500 S

$E_s = 2.1 \cdot 10^8$ kN/m^2
$f_{ym} = 5.0 \cdot 10^5$ kN/m^2
$f_{tm} = 5.5 \cdot 10^5$ kN/m^2
$\varepsilon_{sh} = 0.02$
$\varepsilon_{su} = 0.01$

Concrete: C 85/35

$E_c = 4.04 \cdot 10^7$ kN/m^2
$\nu = 0.20$
$f_{cm} = 8.20 \cdot 10^4$ kN/m^2
$f_{ctm} = 2.88 \cdot 10^3$ kN/m^2

NDCT Niederaussem:
Geometry and material data of cooling tower (ARHPC 85/35)



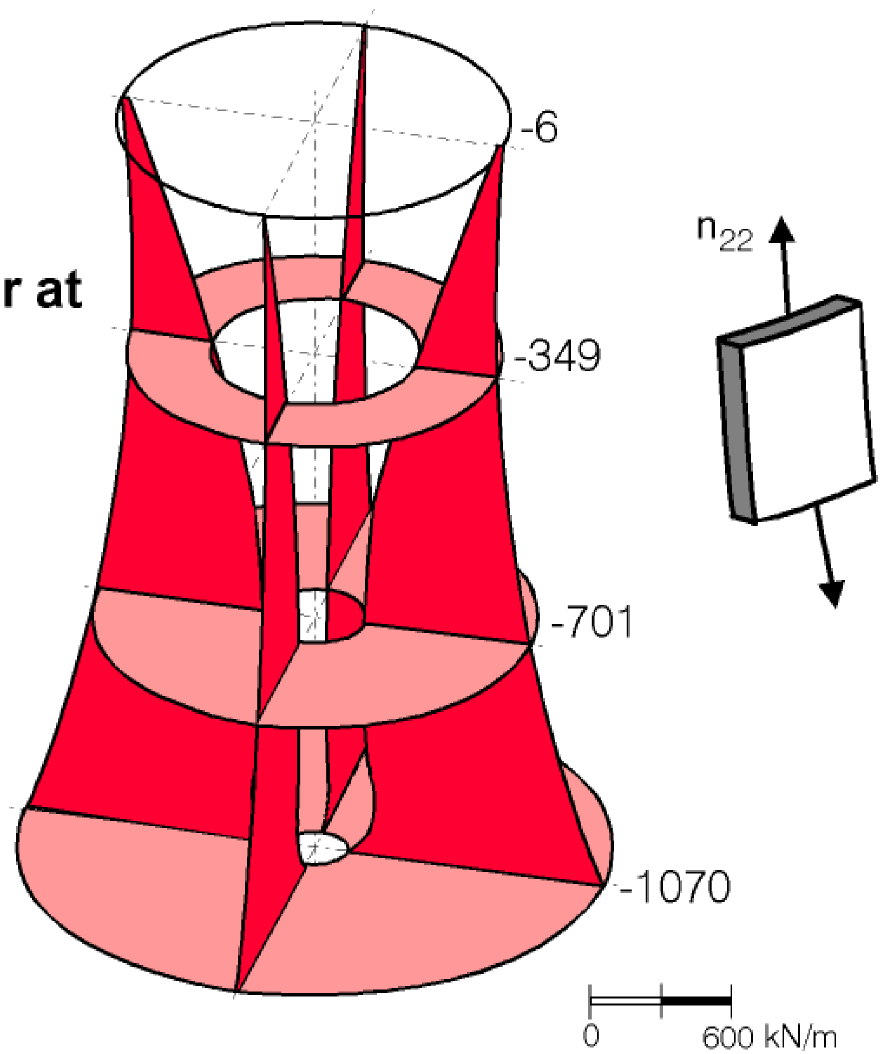
$$r(z) = r_o + a\sqrt{1 + (h_T - z)^2 / b^2}$$

$$\tan\beta_L \geq (r_L - r_T)/(h_T - h_C)$$

NDCT Niederaussem:
Basic dimensions for tower shape optimization

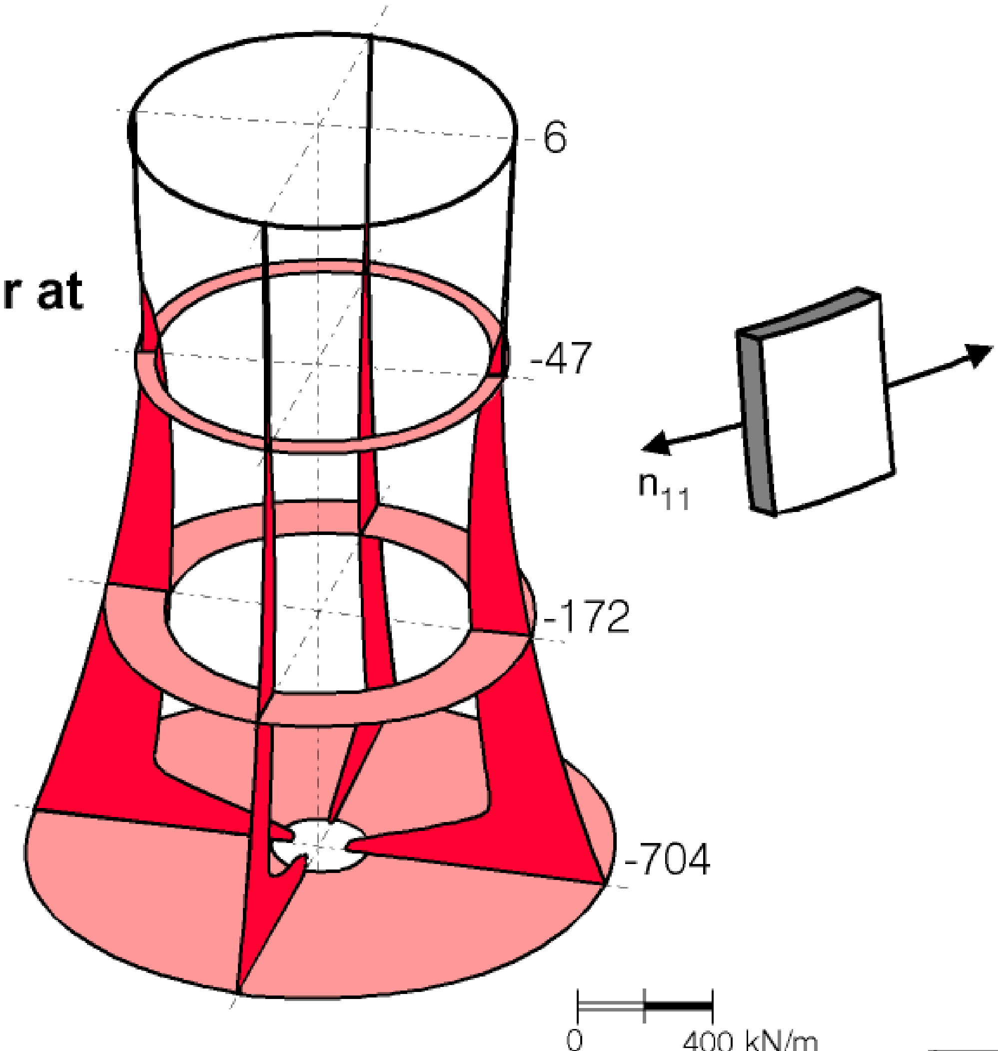
Meridional Forces n_{22g} under Deadweight

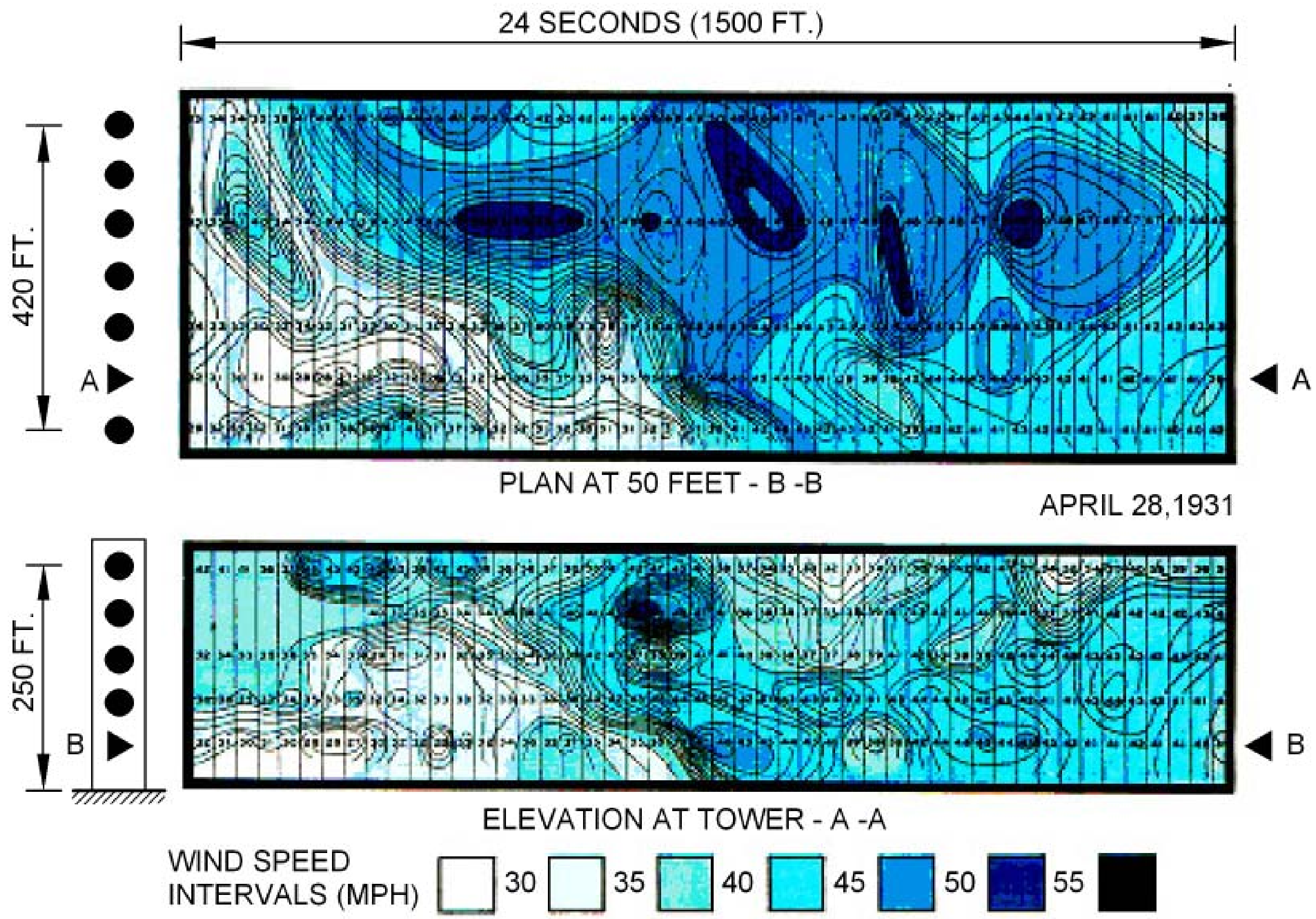
200 m Cooling Tower at KW Niederaussem



Circumferential Forces n_{11g} under Deadweight

200 m Cooling Tower at KW Niederaussem

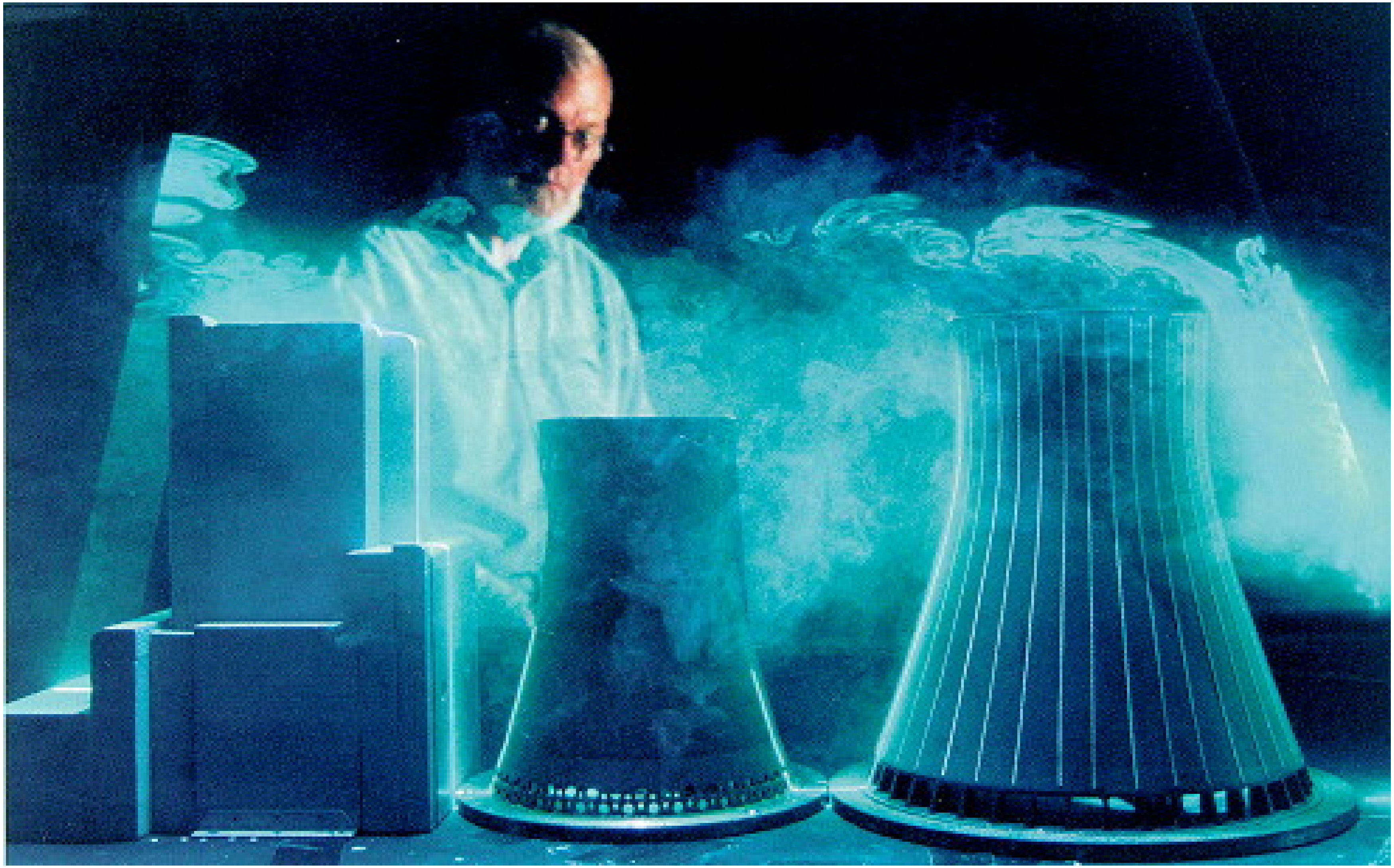




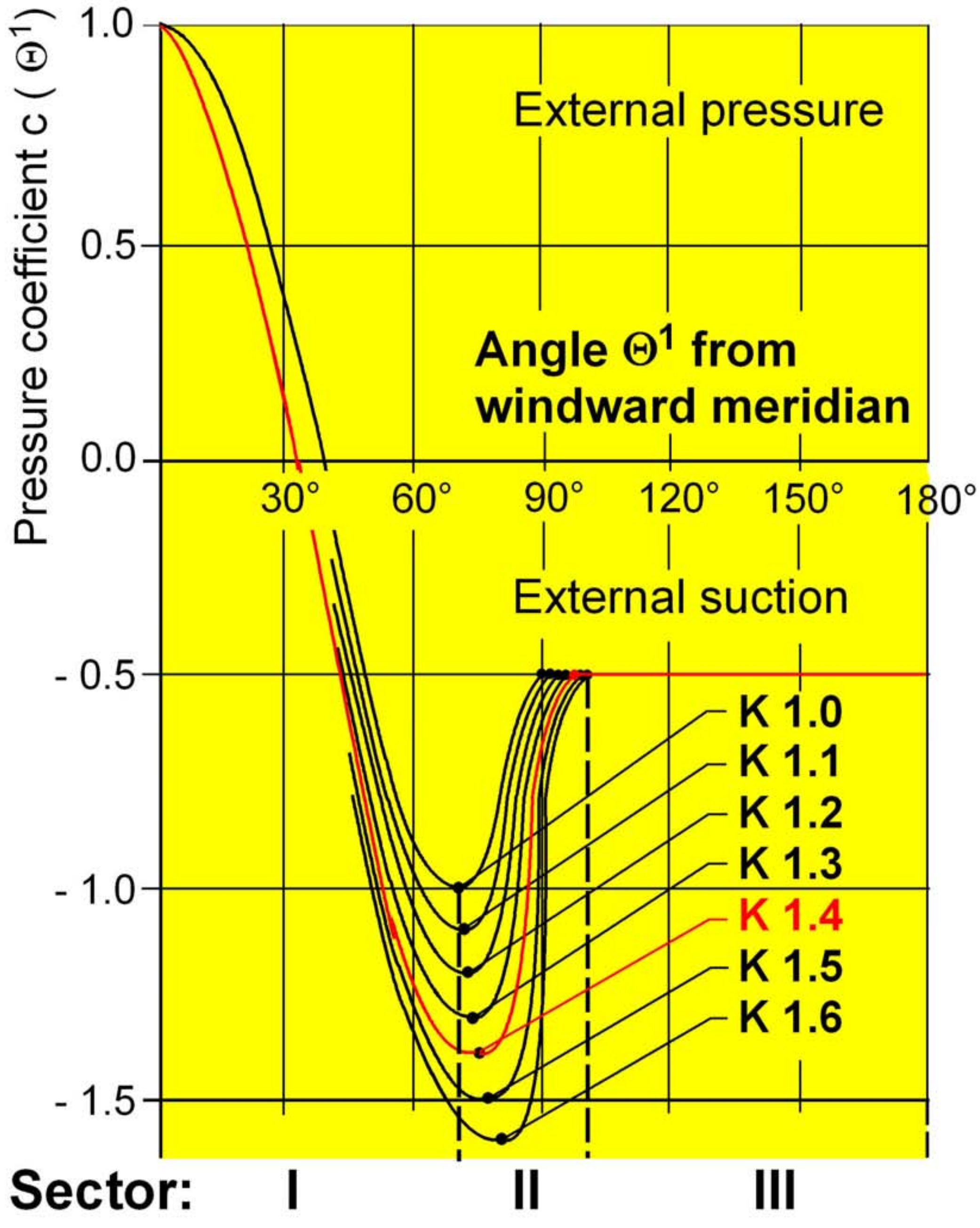
24 Seconds of a storm profile
(R.H. Sherlock, M.B. Stout: J. Aer. Sc. 5(1937), 53 - 61)

Lignite power station Neurath in boundary wind tunnel

Gust modeling in the wind tunnel



NDCT Niederaussem: Types of circumferential wind pressure distribution c (Θ^1)



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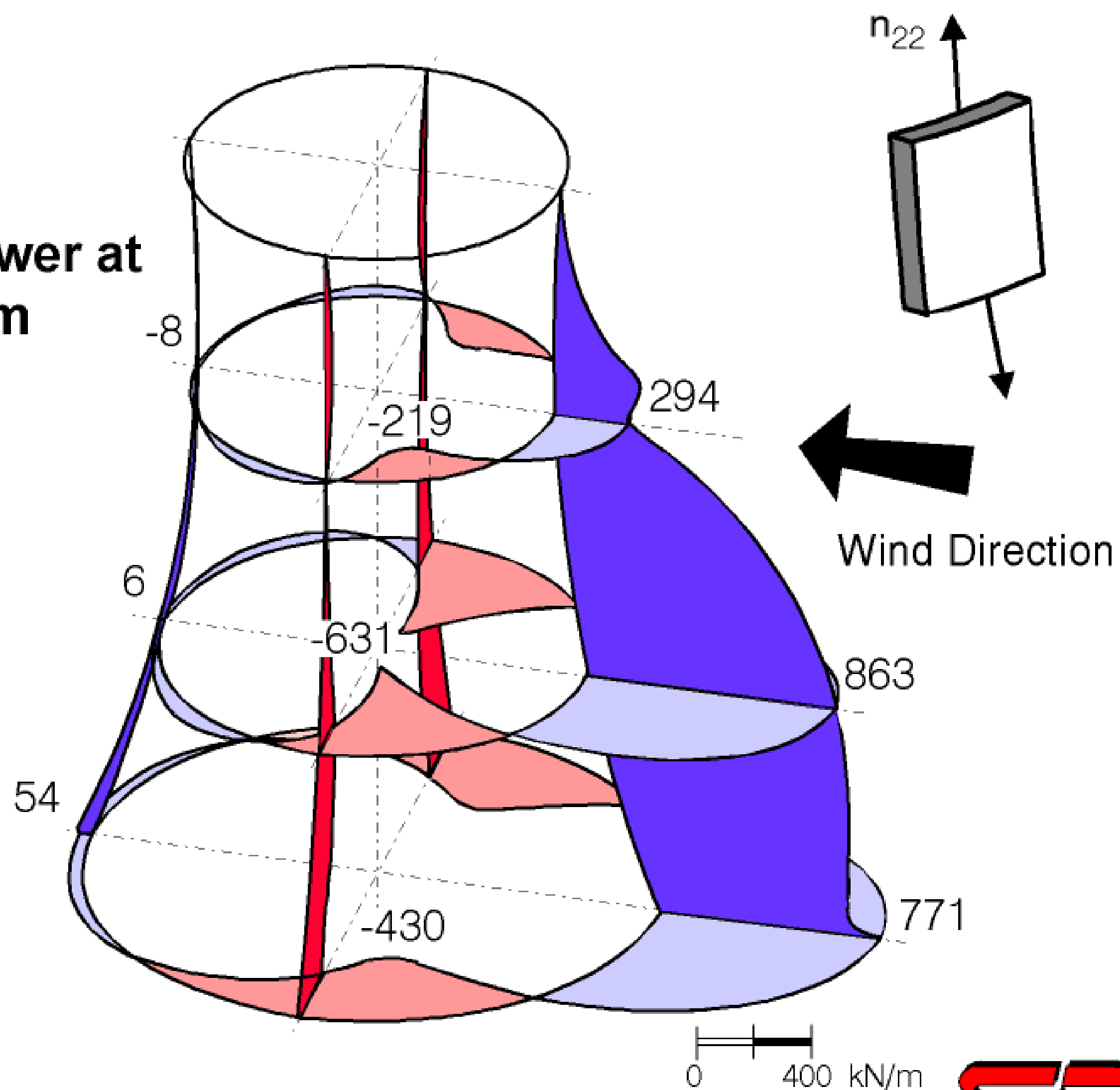
Statik und Dynamik

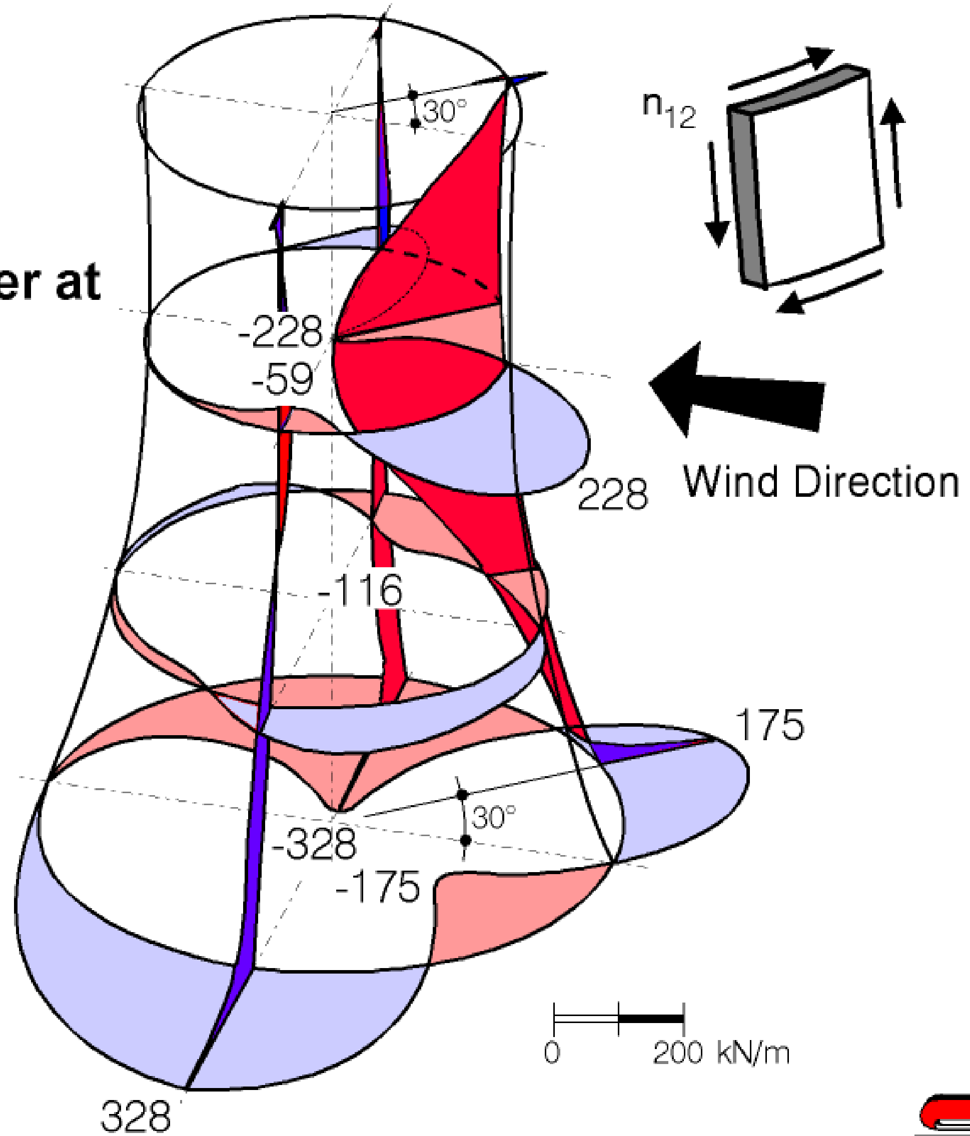
Meridional Forces n_{22W} under Wind Actions

200 m Cooling Tower at KW Niederaussem



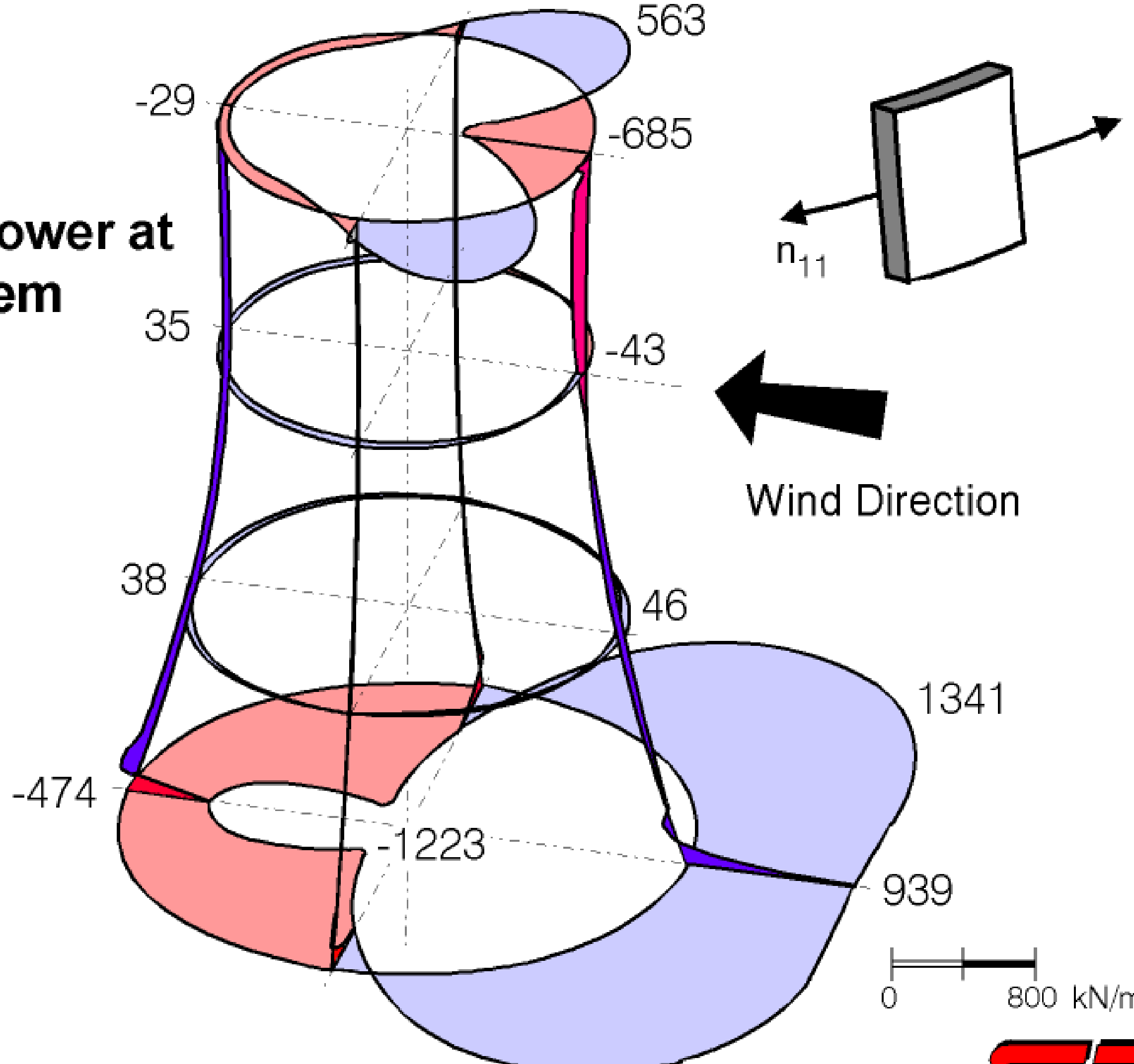
Shear Forces n_{12W} under Wind Actions

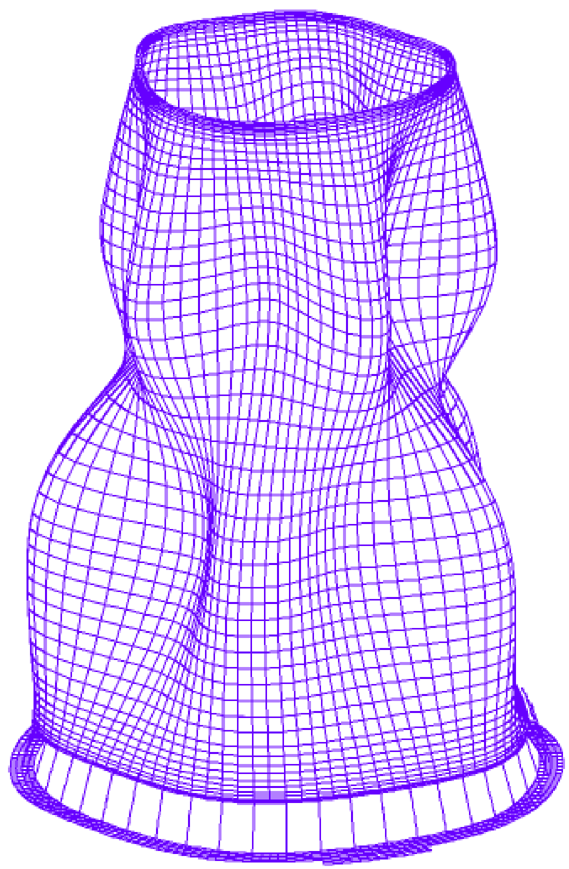
200 m Cooling Tower at KW Niederaussem



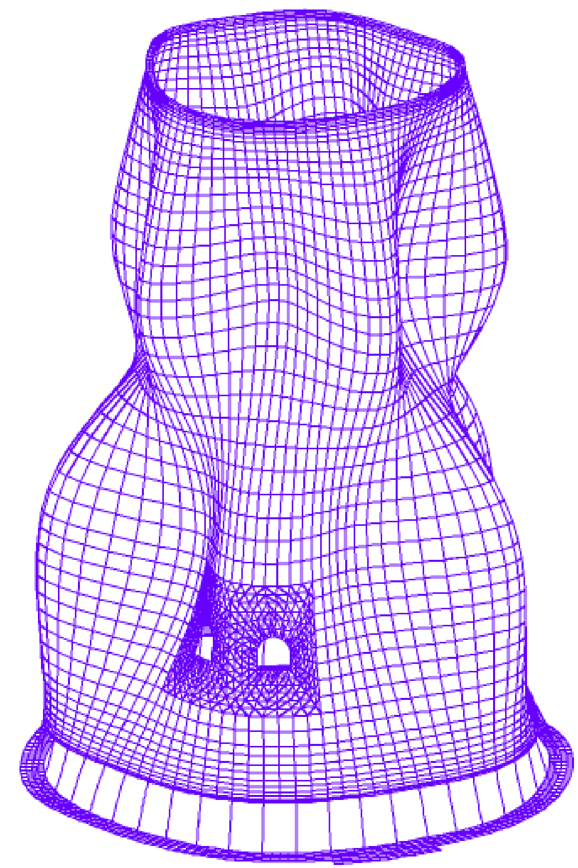
Circumferential Forces n_{11w} under Wind Actions

200 m Cooling Tower at KW Niederaussem



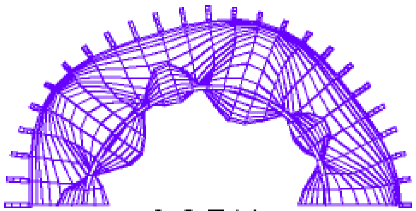
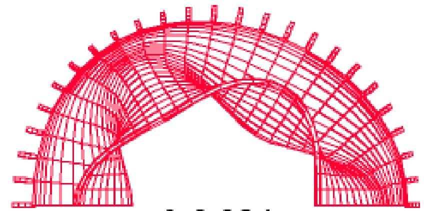
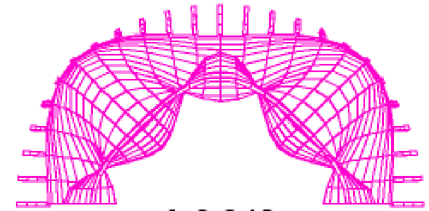
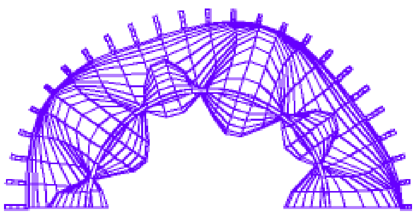
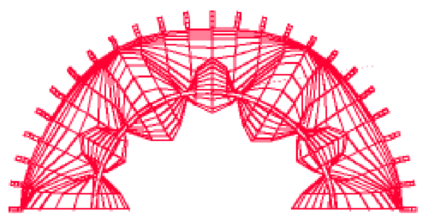
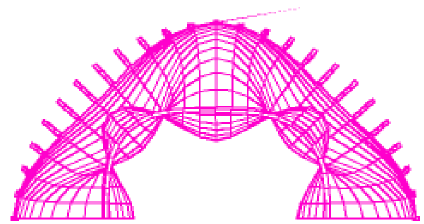
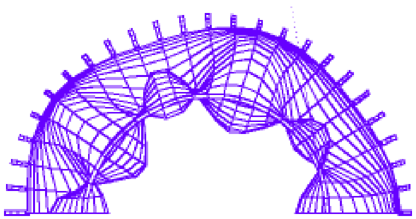
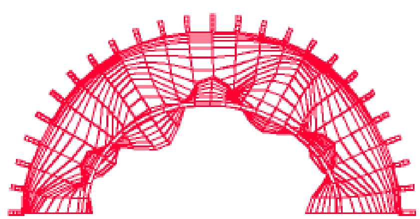
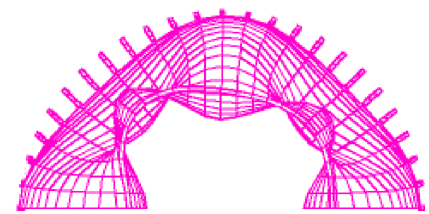


f_{min}= 0.7302 Hz

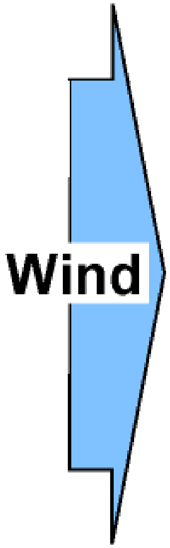


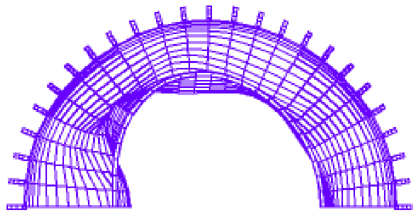
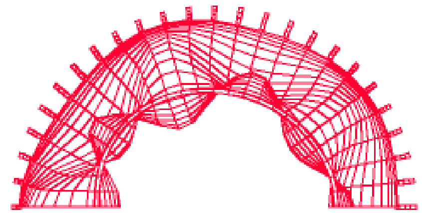
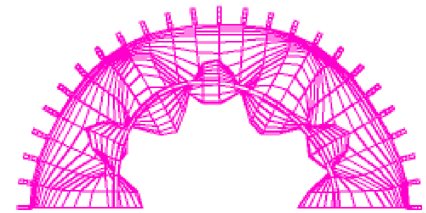
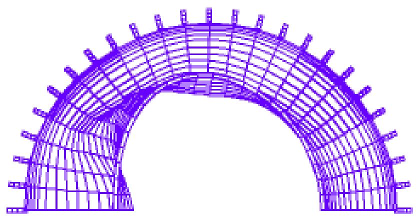
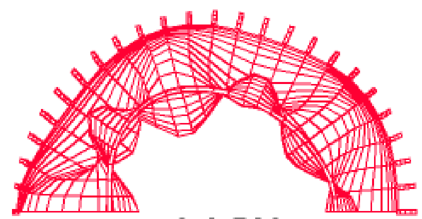
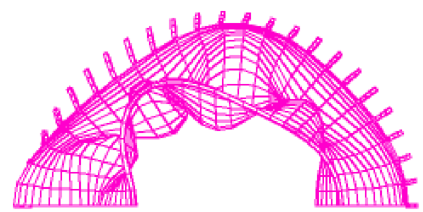
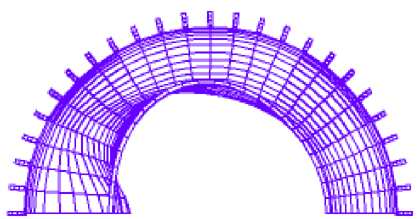
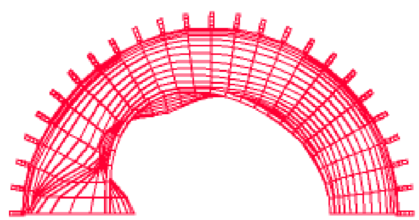
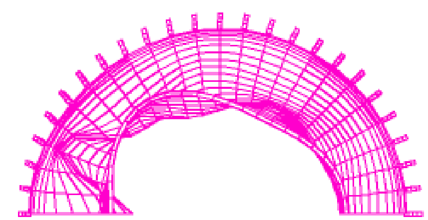
f_{min}= 0.7335 Hz

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

	1^{st} mode	2^{nd} mode	3^{rd} mode	Load
	 f=0.711	 f=0.834	 f=0.846	G
	 f=0.593	 f=0.682	 f=0.790	G + ΔT_{45K}
	 f=0.599	 f=0.709	 f=0.733	G + ΔT_{45K} + 1.0 W

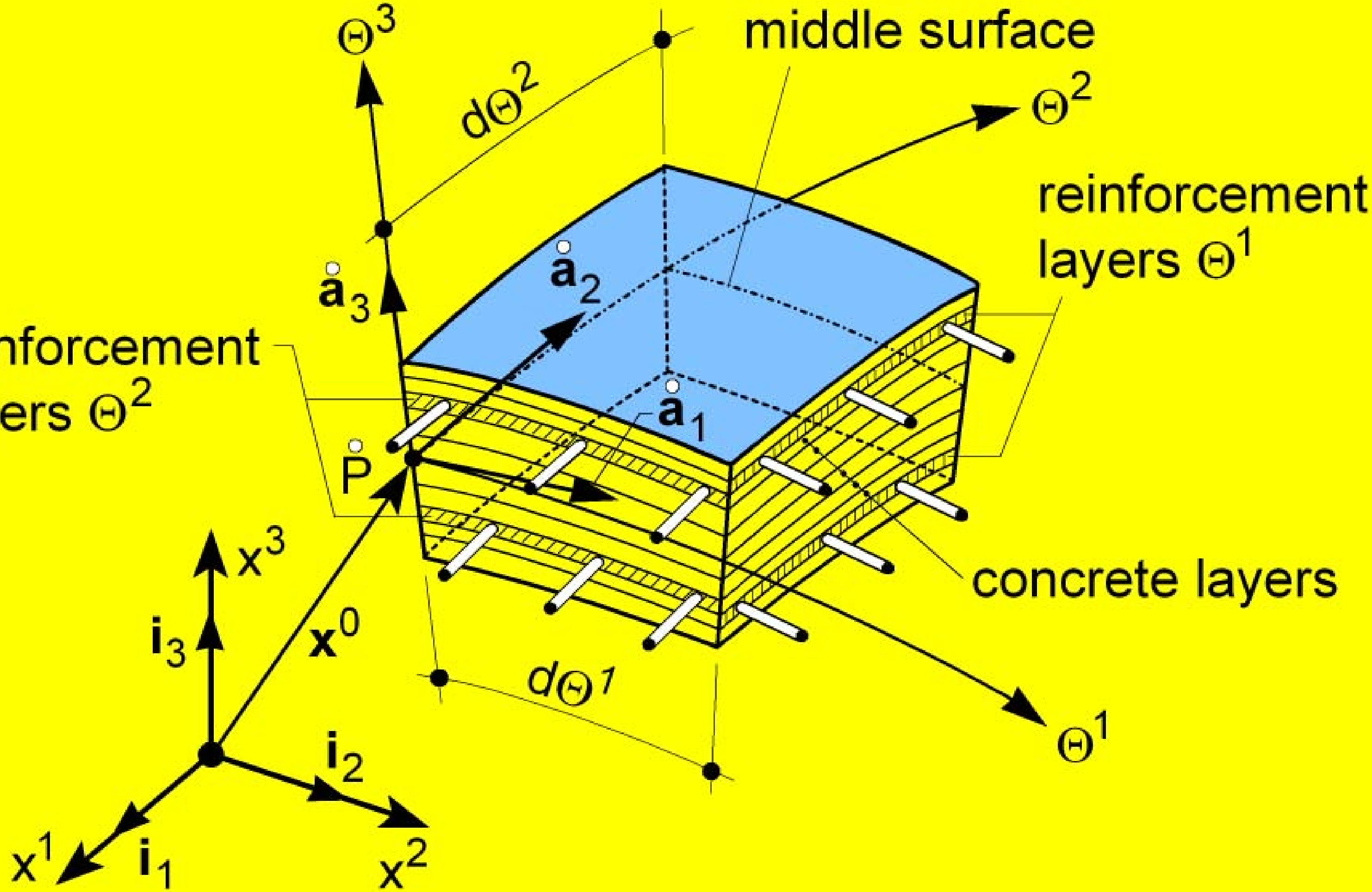
NDCT Niederaussem:
Change of natural modes due to crack damage



1^{st} mode	2^{nd} mode	3^{rd} mode	Load
 f=0.586	 f=0.590	 f=0.715	G + ΔT_{45K} + 1.2 W
 f=0.439	 f=0.568	 f=0.688	G + ΔT_{45K} + 1.5 W
 f=0.192	 f=0.367	 f=0.517	G + ΔT_{45K} + 2.3 W

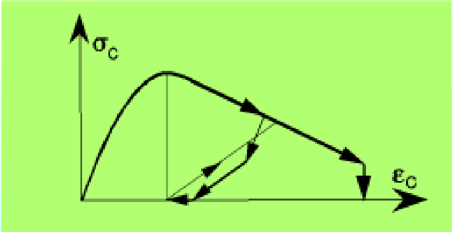
NDCT Niederaussem:
Change of natural modes due to crack damage

NDCT Vattenfall Lignite Power Plant Boxberg 2008

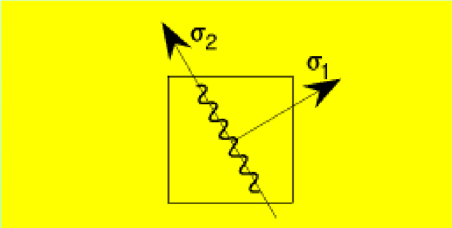


Layered model of reinforced concrete shell

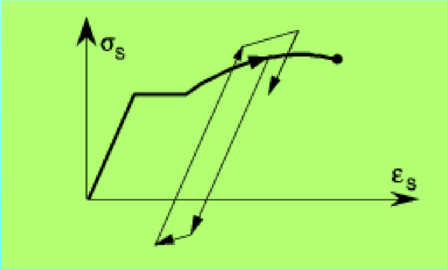
- Nonlinear stress - strain relationship in compression



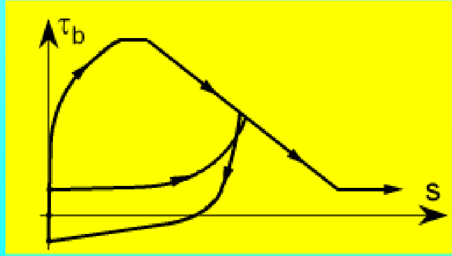
- Tension cracking



- Yielding of reinforcement

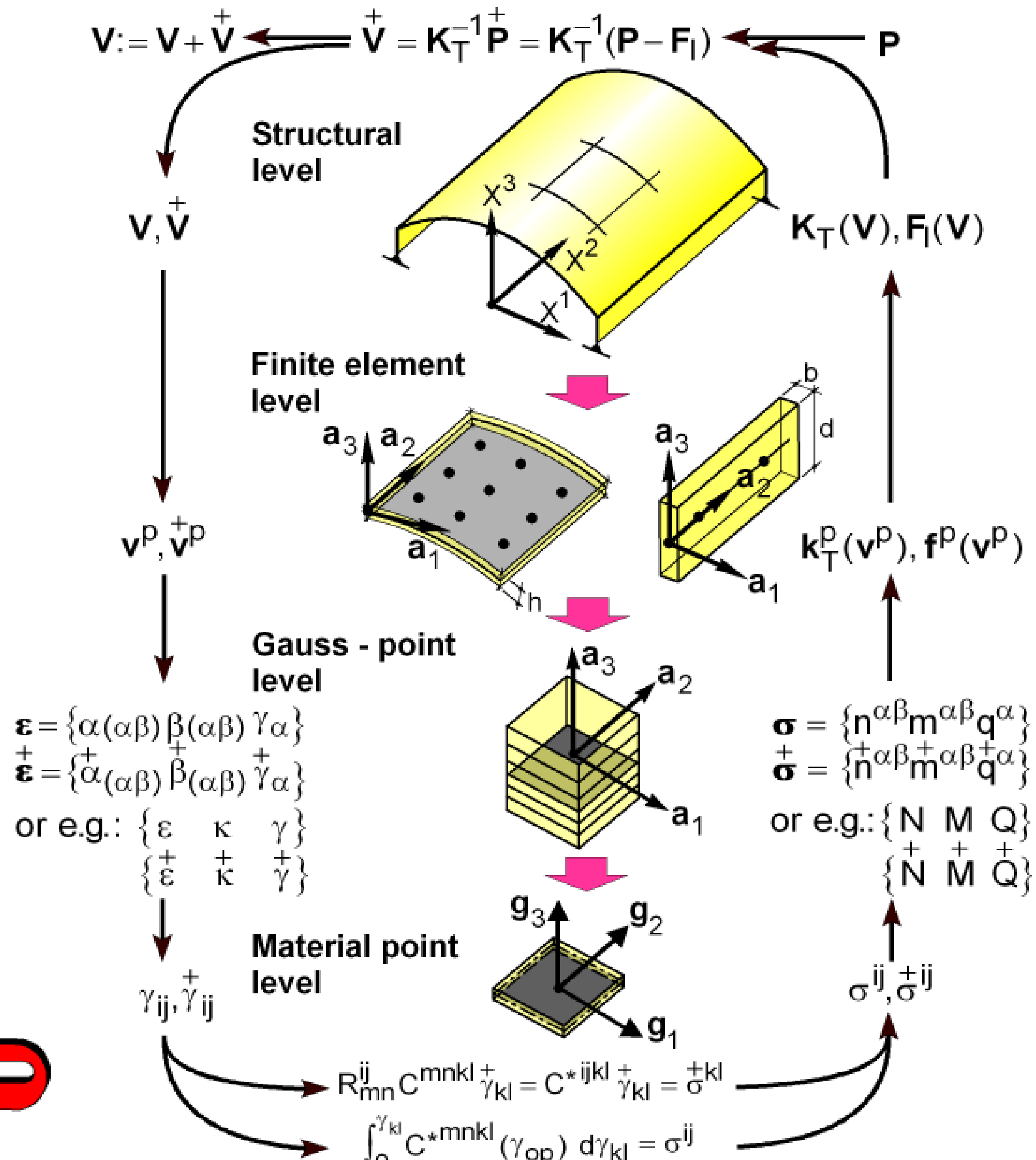


- Nonlinear concrete - steel bond



Nonlinear behavior of reinforced concrete including material damage

Sets of variables and iterations



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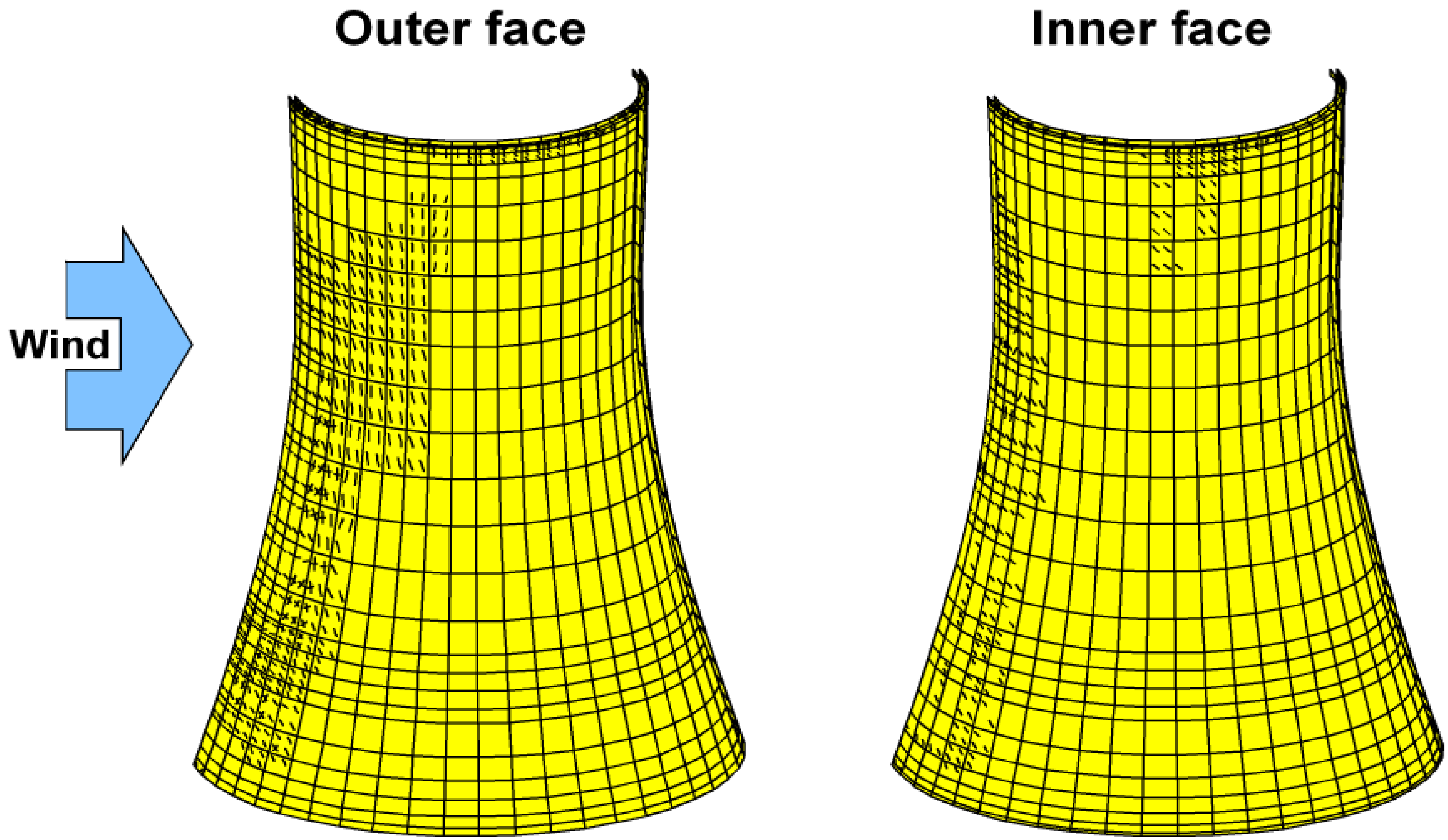
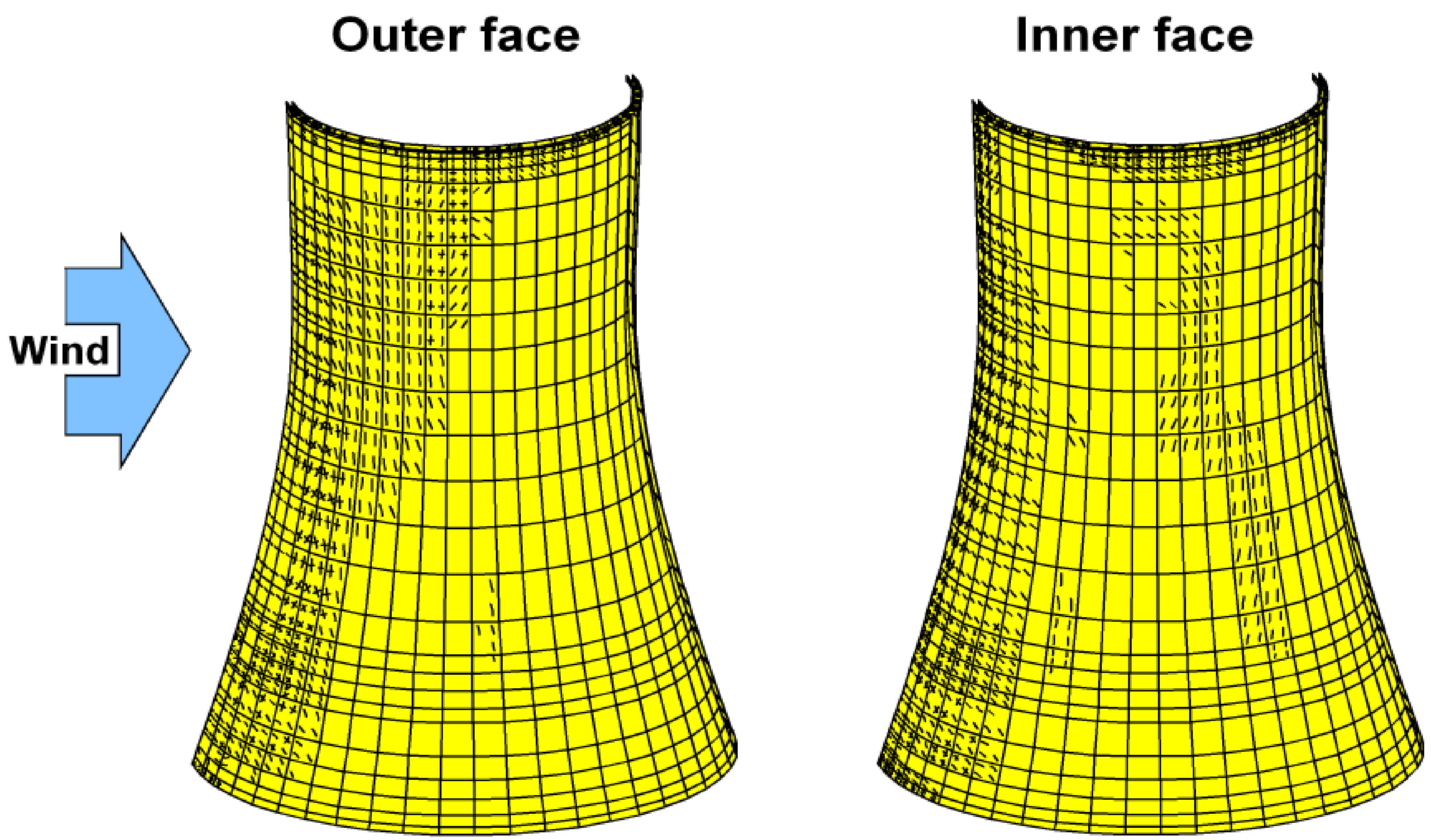
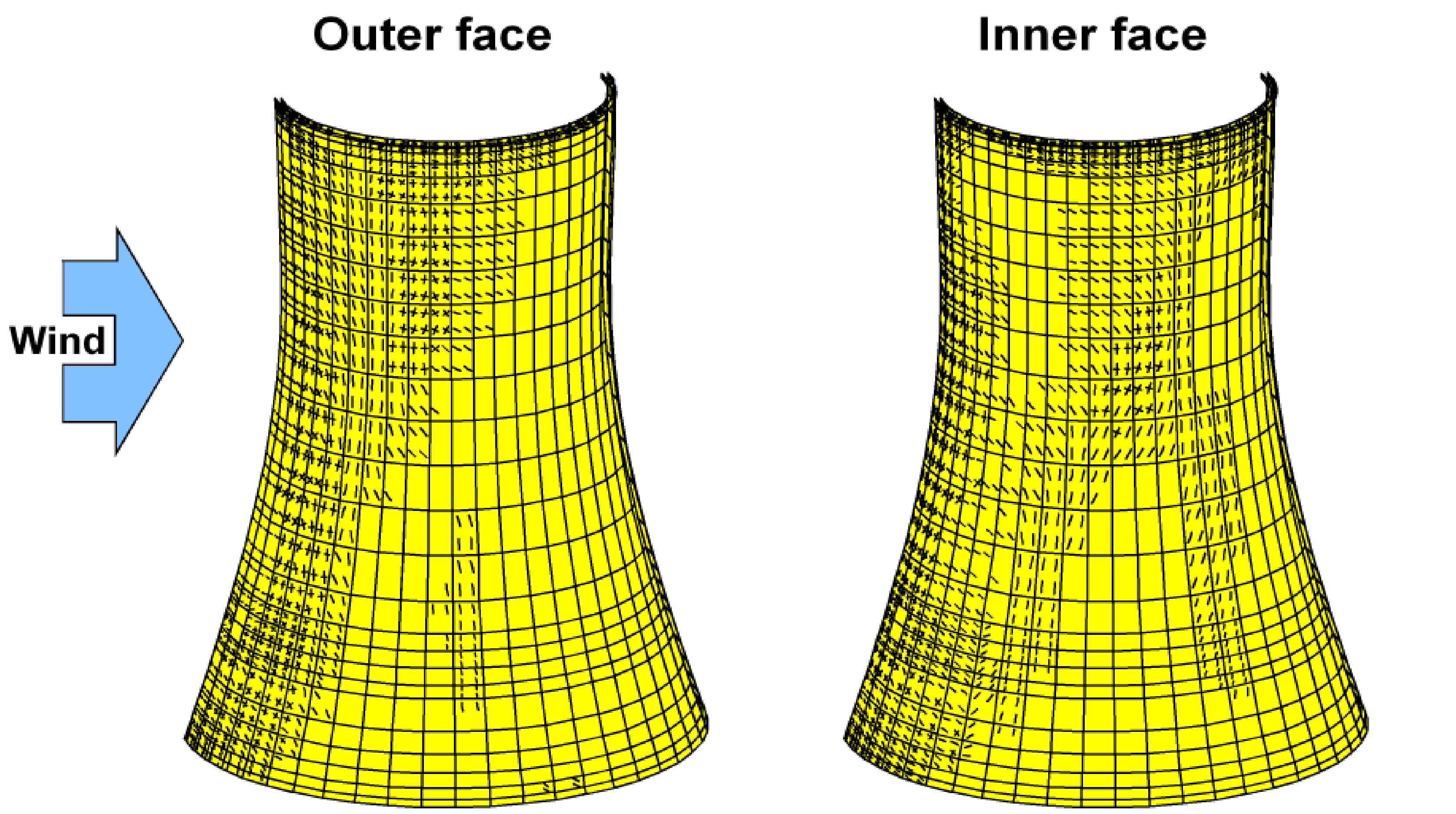


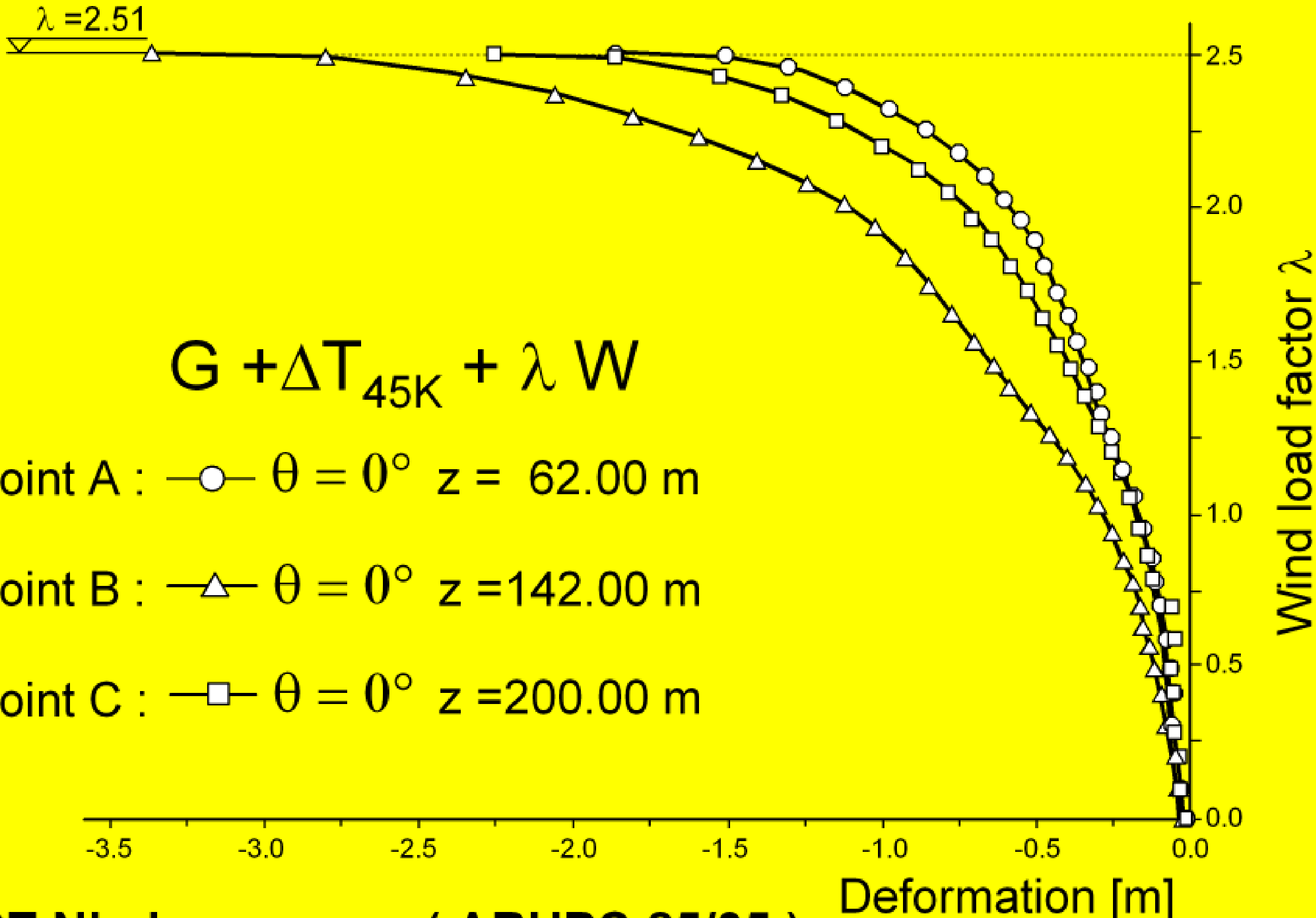
NDCT Niederaussem (ARHPC 85/35):
Crack patterns at D + 1.48 W; w > 0.00 mm



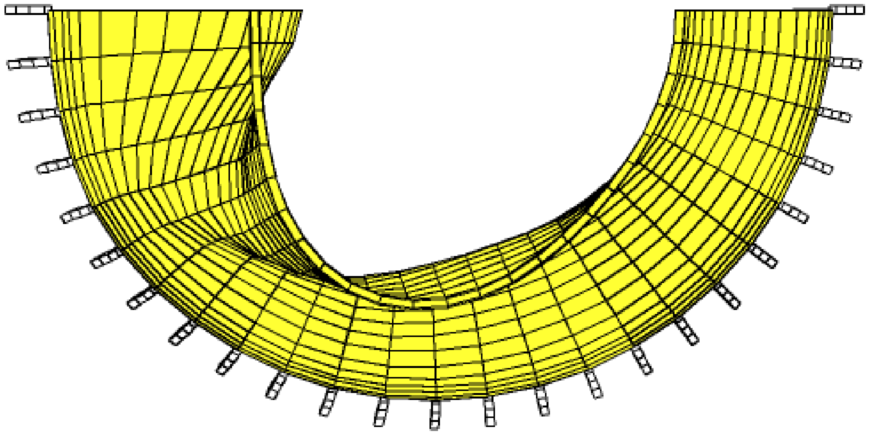
NDCT Niederaussem (ARHPC 85/35):
Crack patterns at D + 2.03 W; w > 0.00 mm

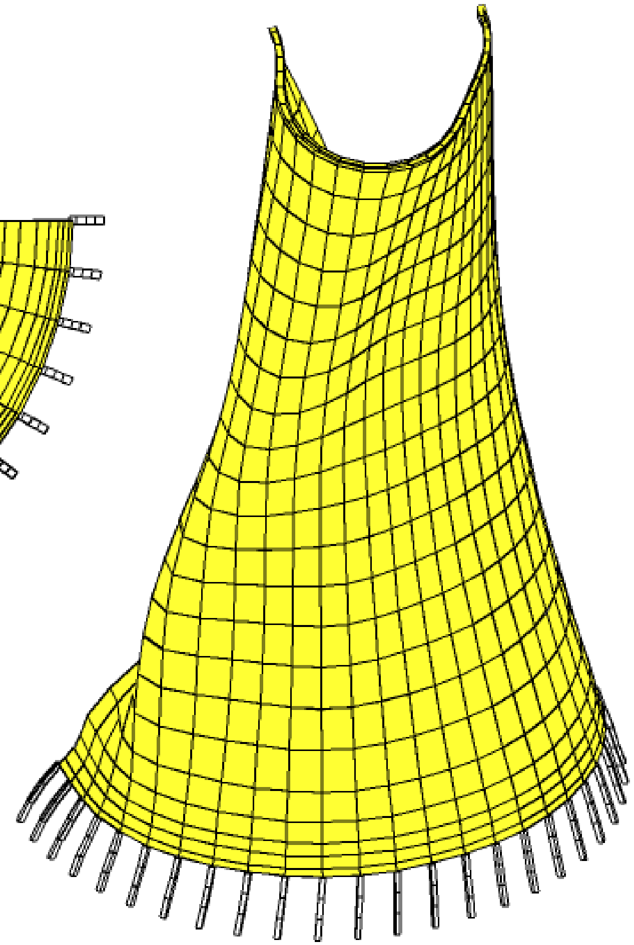


NDCT Niederaussem (ARHPC 85/35):
Crack patterns at D + 2.51 W; w > 0.00 mm

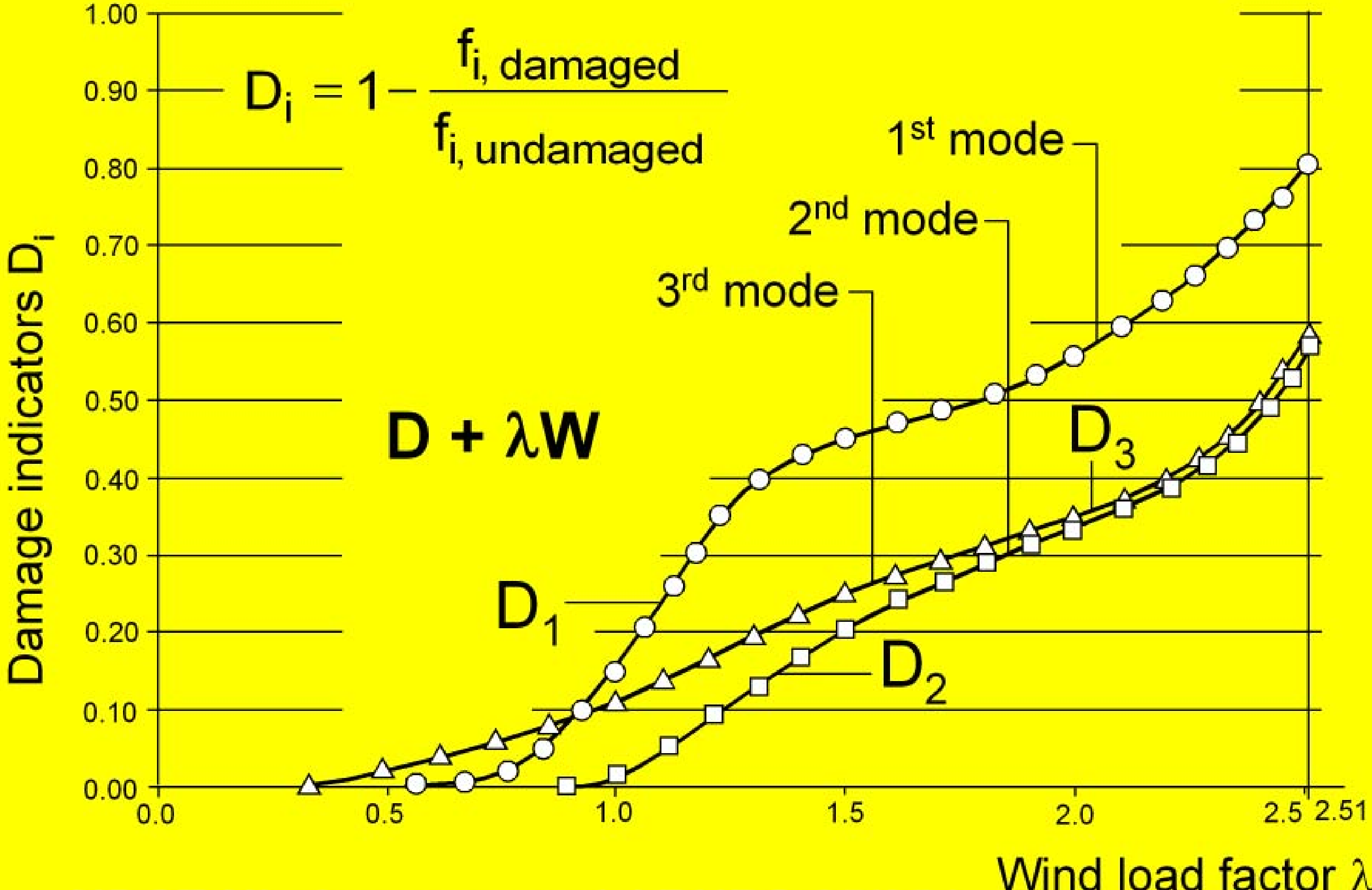


NDCT Niederaussem: (ARHPC 85/35)
Load - deformation curves at points A, B and C

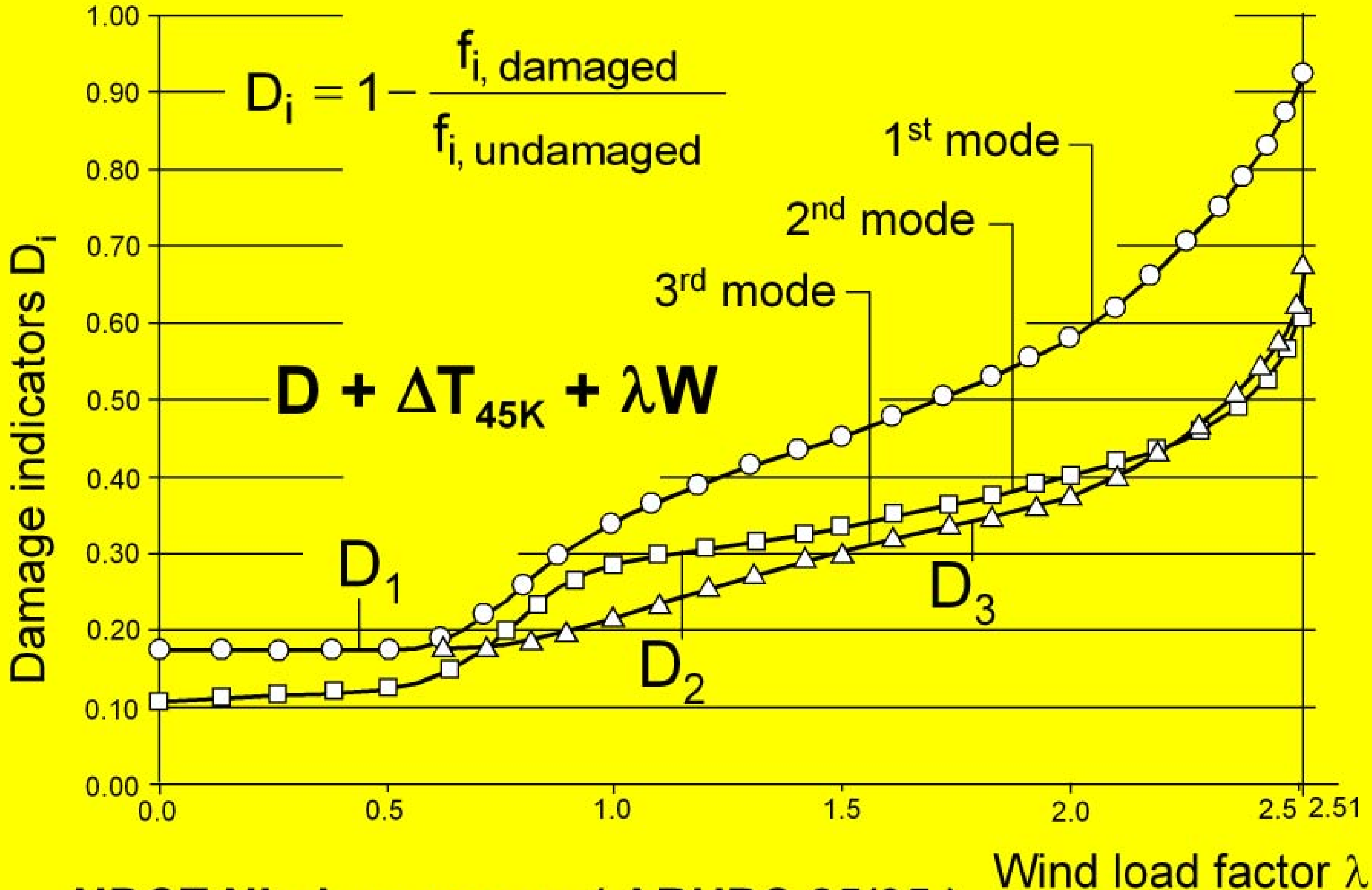




NDCT Niederaussem:
30 - times exaggerated deformation at G + ΔT_{45K} + 2.30 W



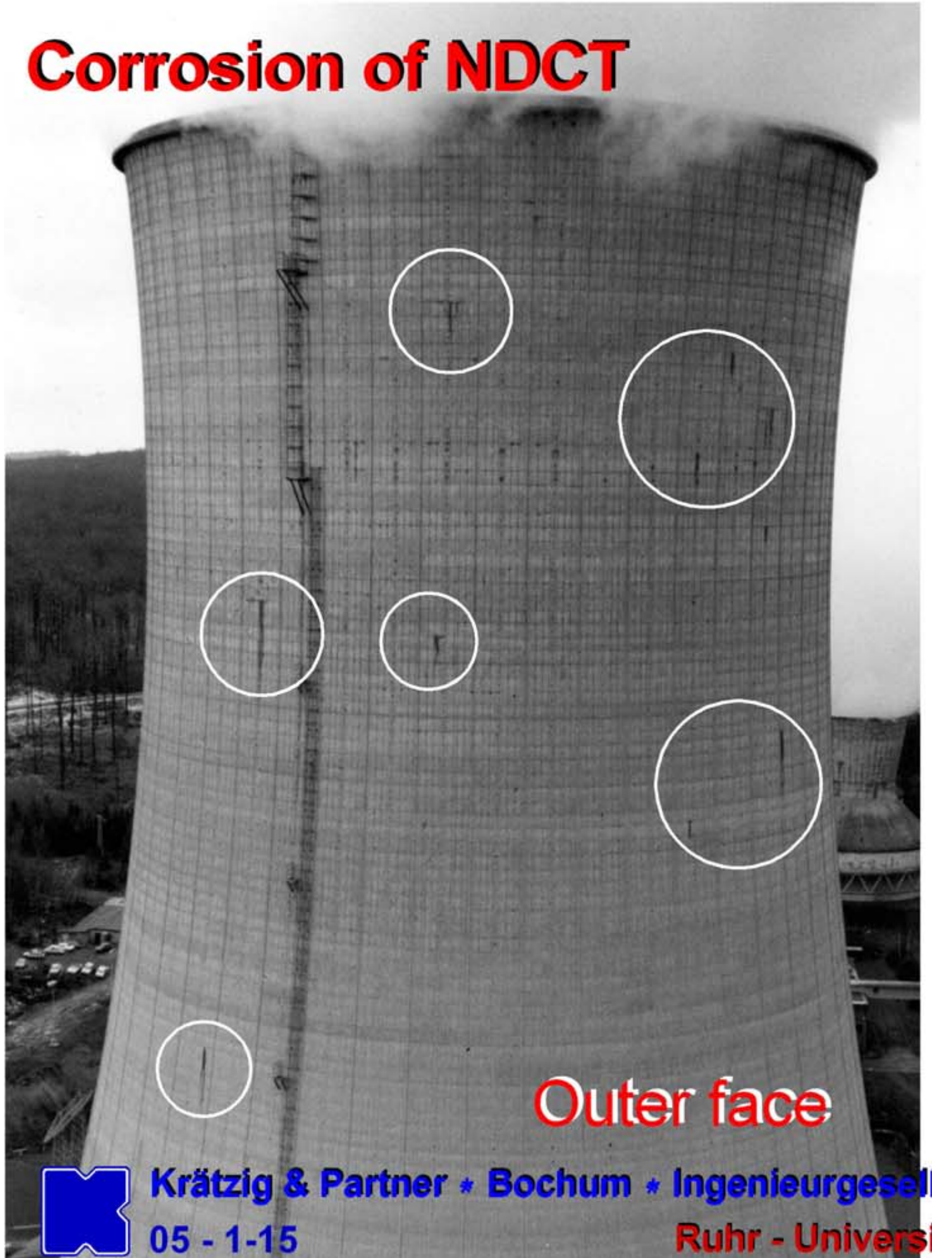
NDCT Niederaussem: (ARHPC 85/35)
First 3 damage indicators for $D + \lambda W$



NDCT Niederaussem: (ARHPC 85/35)

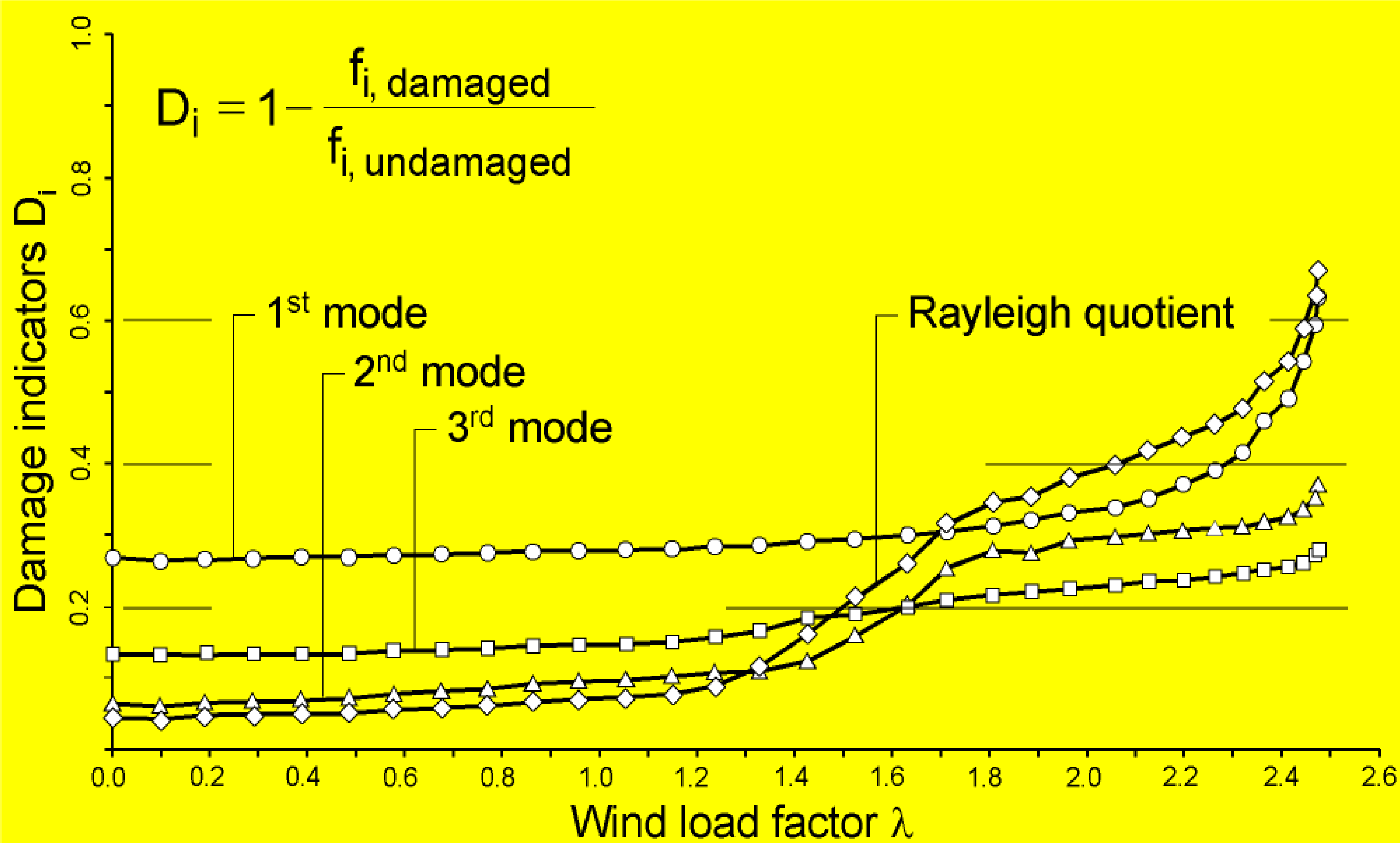
First 3 damage indicators for $D + \Delta T_{45K} + \lambda\ W$

Corrosion of NDCT



Reduction of	Dimensions		Stiffness		Strength	
Deterioration due to:	concrete	steel	concrete	steel	concrete	steel
1. Carbonation		●				
2. Chloride penetration		●	○			
3. Sulfade attack	●		●		●	
4. Abrasion, erosion	●	●				
5. Freeze-thaw-cycles			●		●	
6. Fire: permanent ●, during fire ○	●		●	○	●	○

Mechanistic empirial deterioration models for RC members



NDCT Goesgen: First 3 damage indicators: $G+\Delta T_{45K}+\Delta T_{hygr}+\lambda W$

Load combination:

Ultimate monotonic load factor λ_{crit} : D+λW   D+ΔT_{45K}+λW

	D+λW	D+ΔT_{45K}+λW
λ_{crit}	1.71	1.68

Wind load histories:

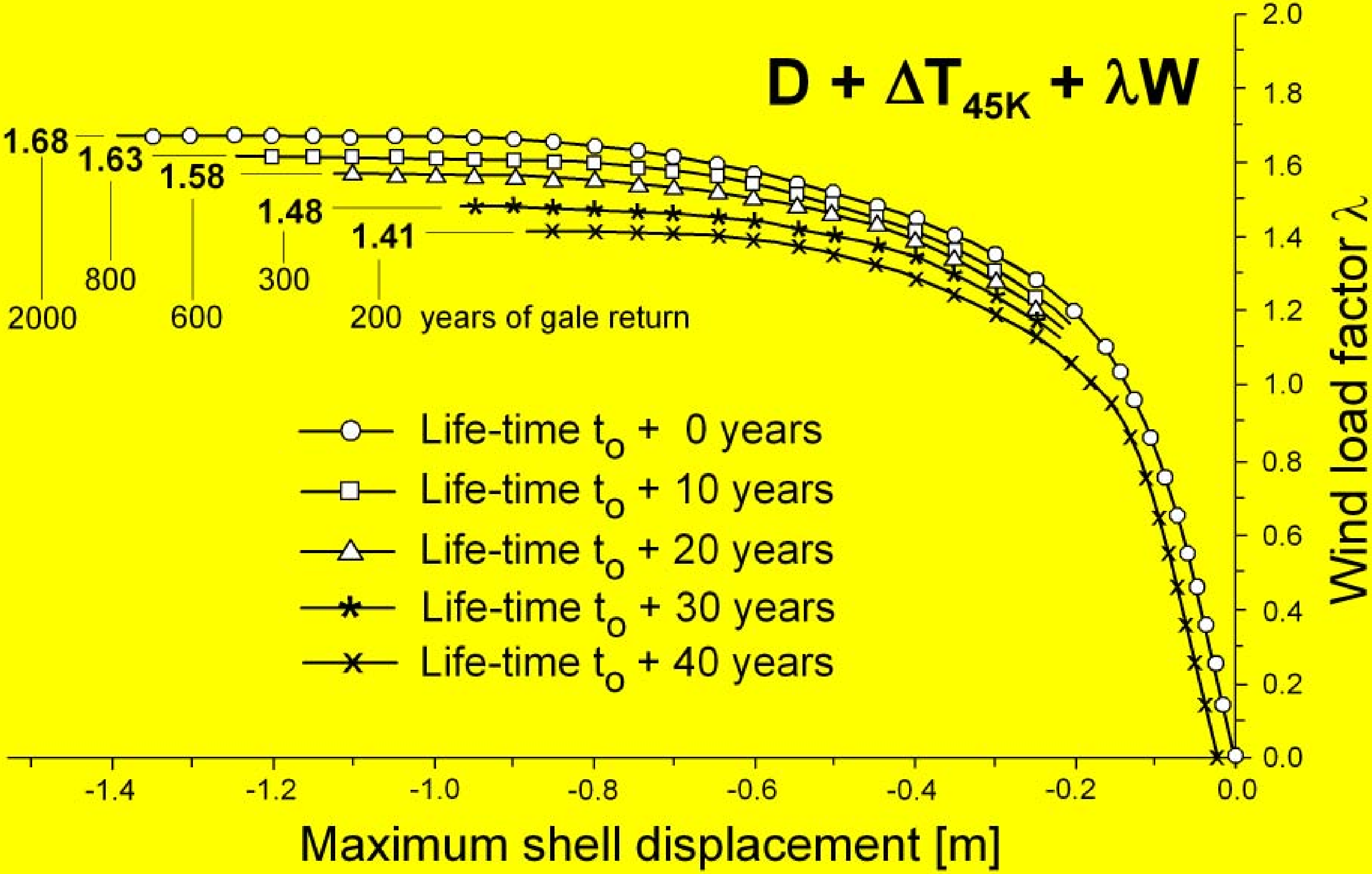
t = 0: One initial gale — $\lambda_{init} = 1.20$ $\lambda_{init} = 0.95$

t = 10•20•30•40 years: one further gale of $\lambda = 1.00$

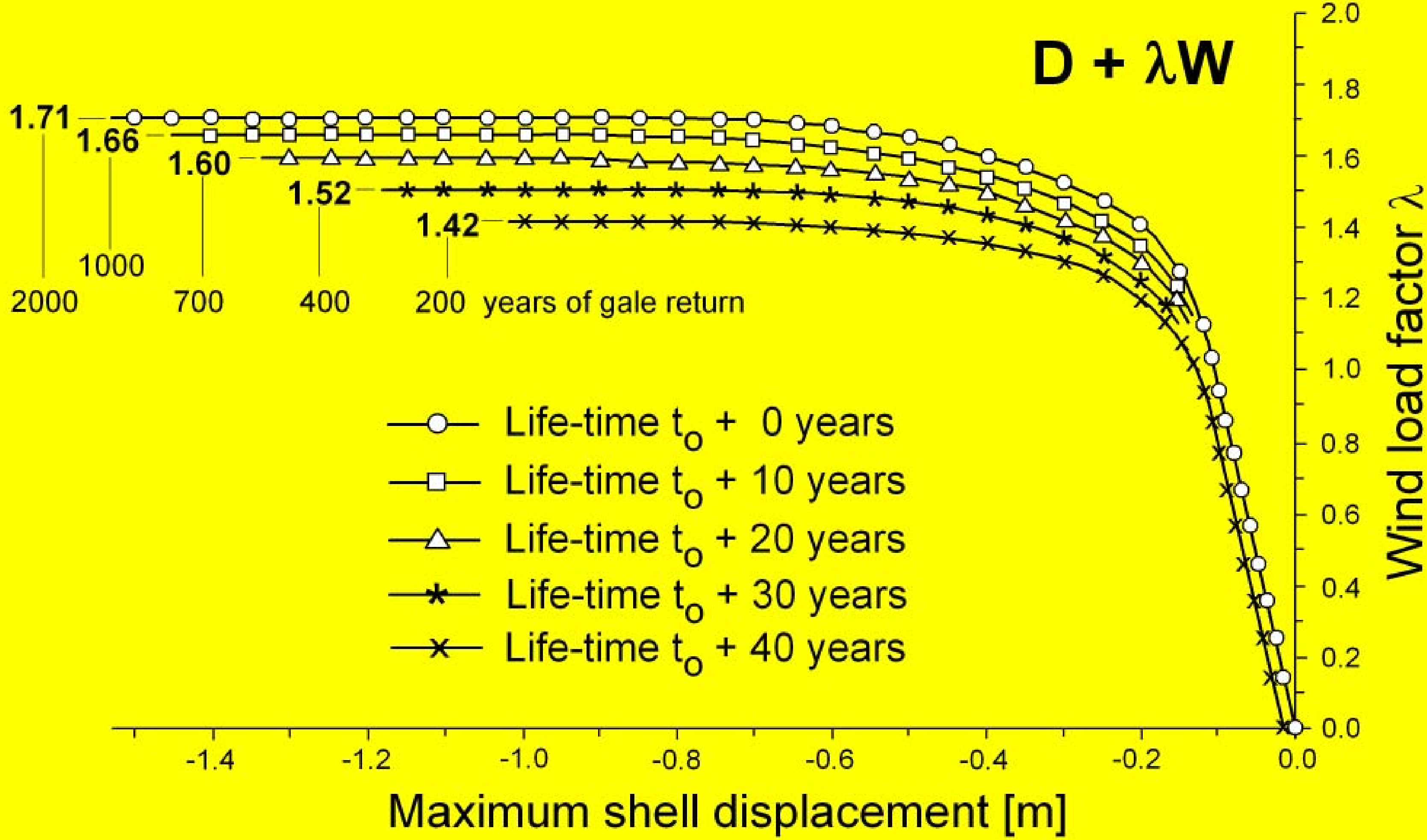
Corrosion histories:

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

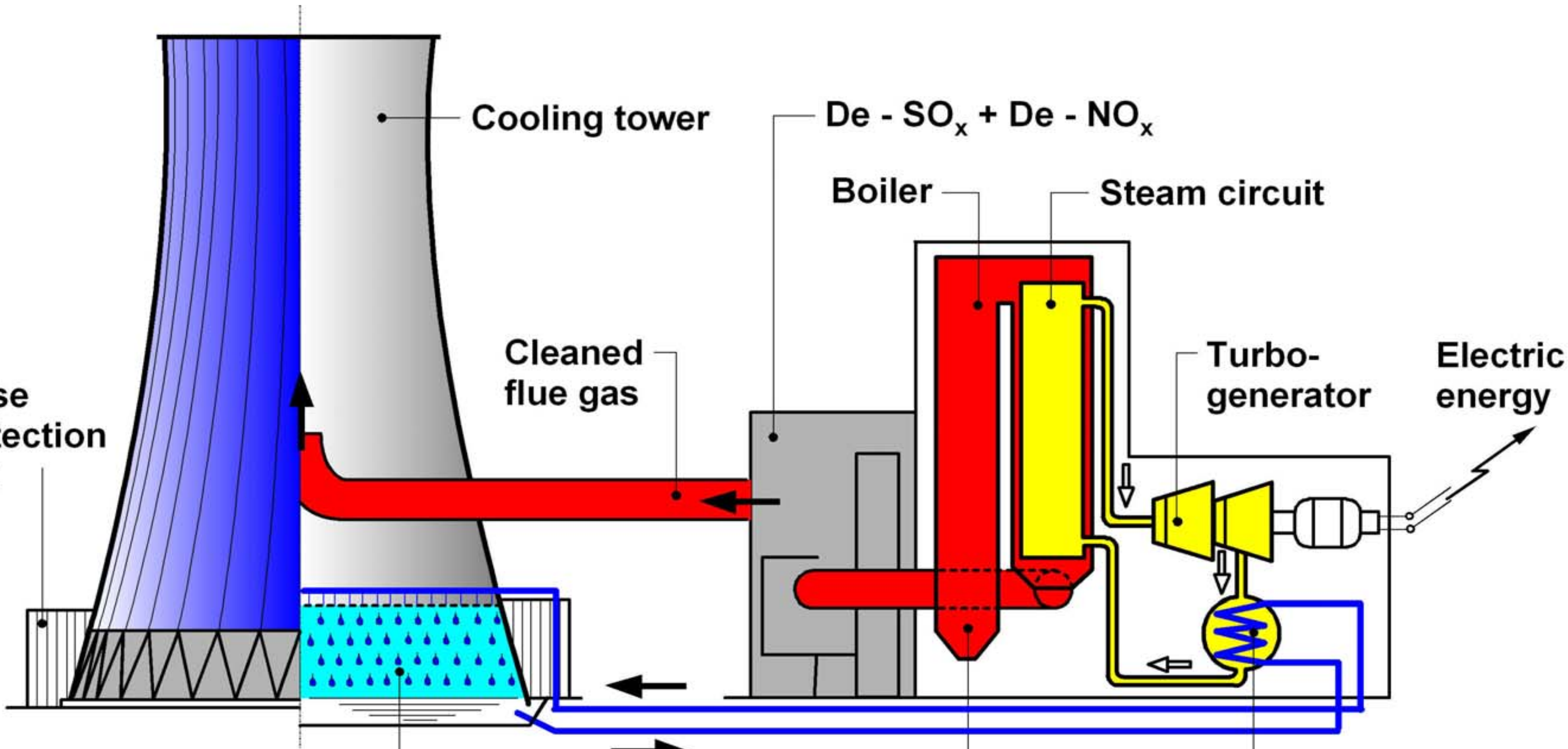


Life-time simulations

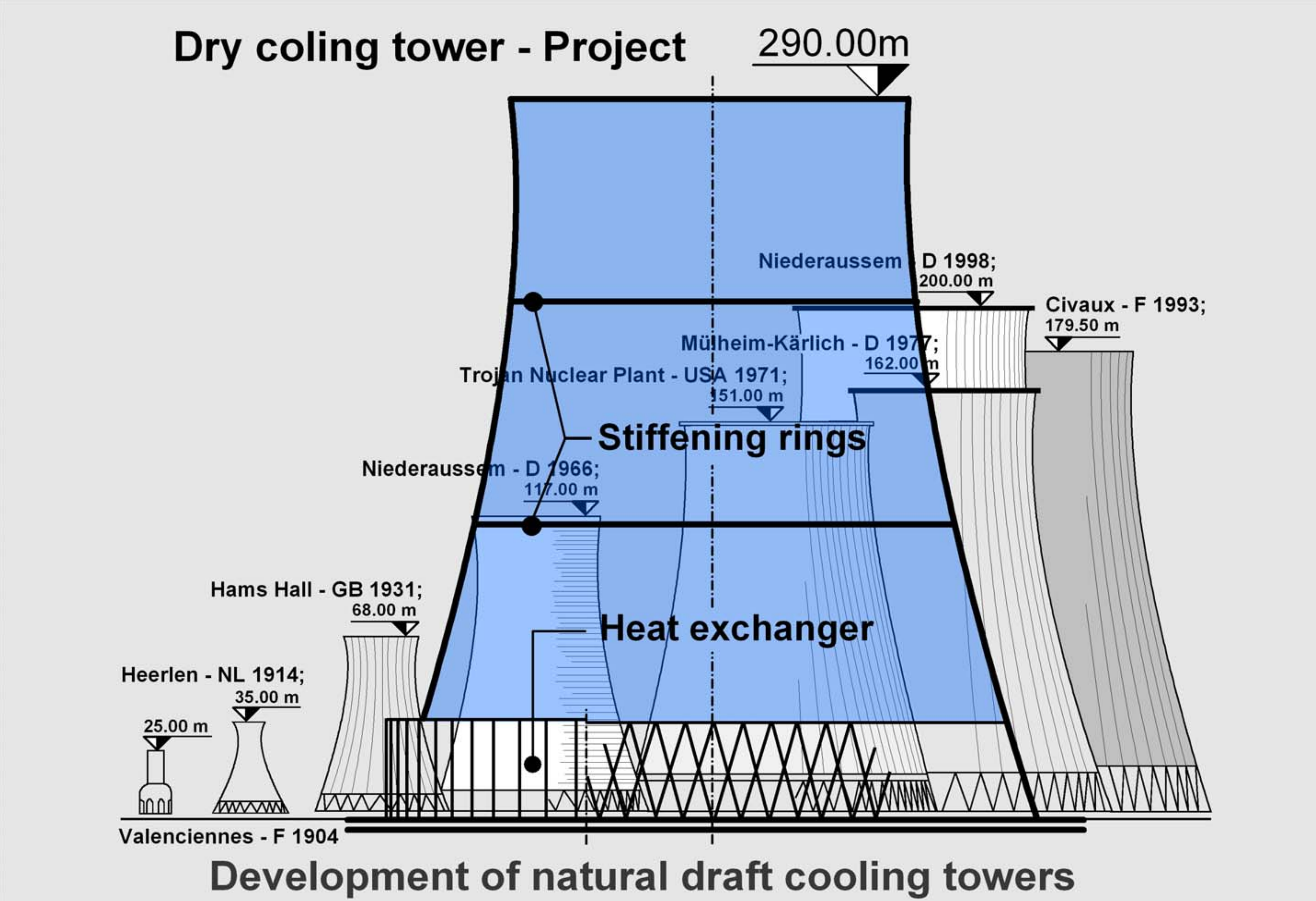


Life-time simulations

NDCT RWE Lignite Power Plant Neurath 2007



Thermal power plant with cleaned flue gas injection



Dry coling tower - Project
290.00m
Niederaussem - D 1998;
200.00 m
Civaux - F 1993;
179.50 m
Mülheim-Kärlich - D 1977;
162.00 m
Trojan Nuclear Plant - USA 1971;
151.00 m
Stiffening rings
Niederaussem - D 1966;
117.00 m
Hams Hall - GB 1931;
68.00 m
Heat exchanger
Heerlen - NL 1914;
35.00 m
25.00 m
Valenciennes - F 1904
Development of natural draft cooling towers

Wilfried B. Krätzig, Reinhard Harte, Ralf Wörmann:

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**

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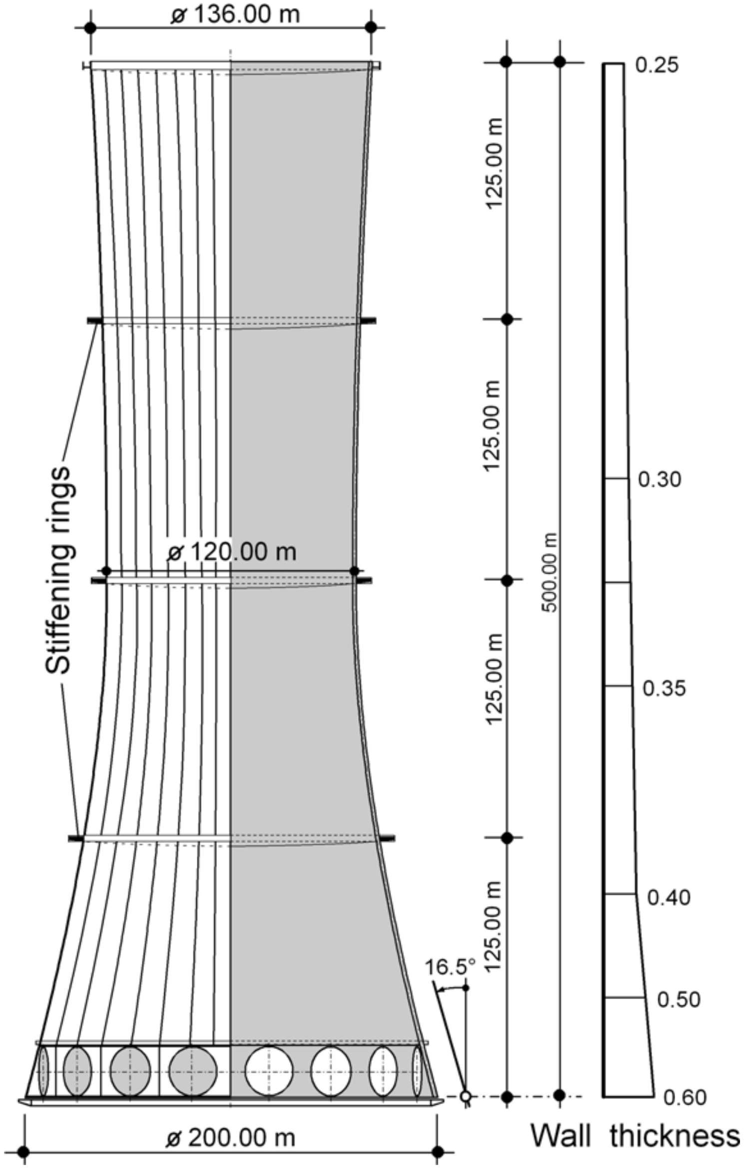
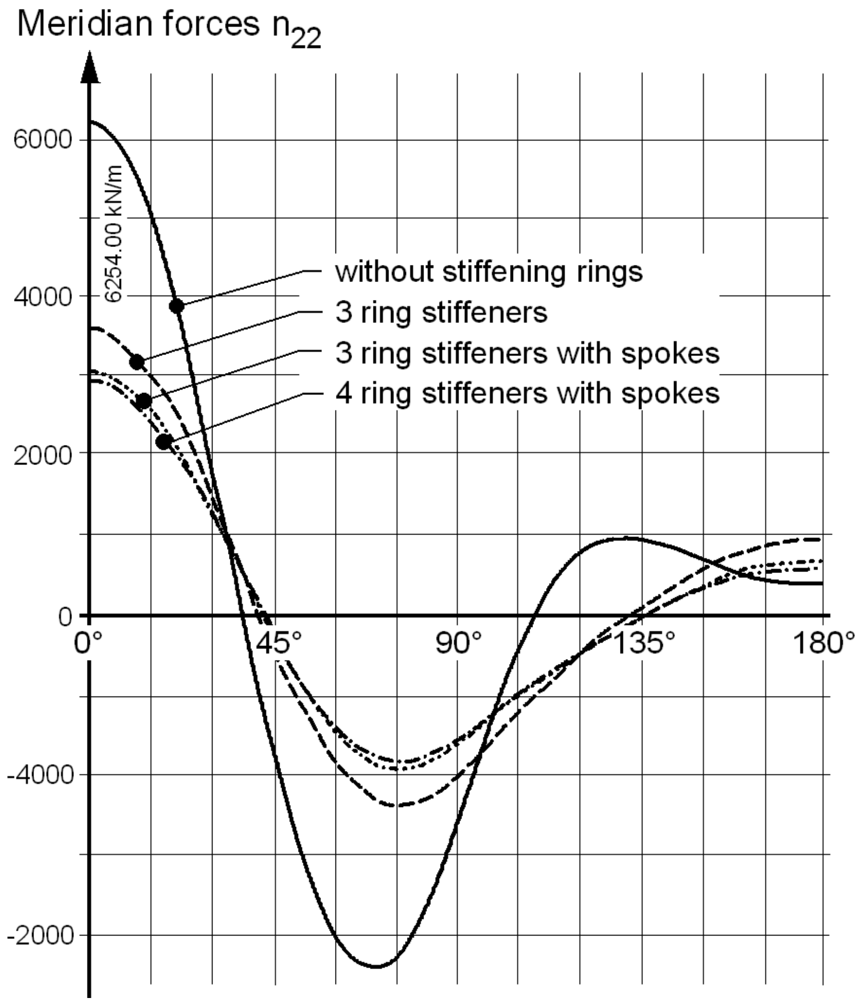
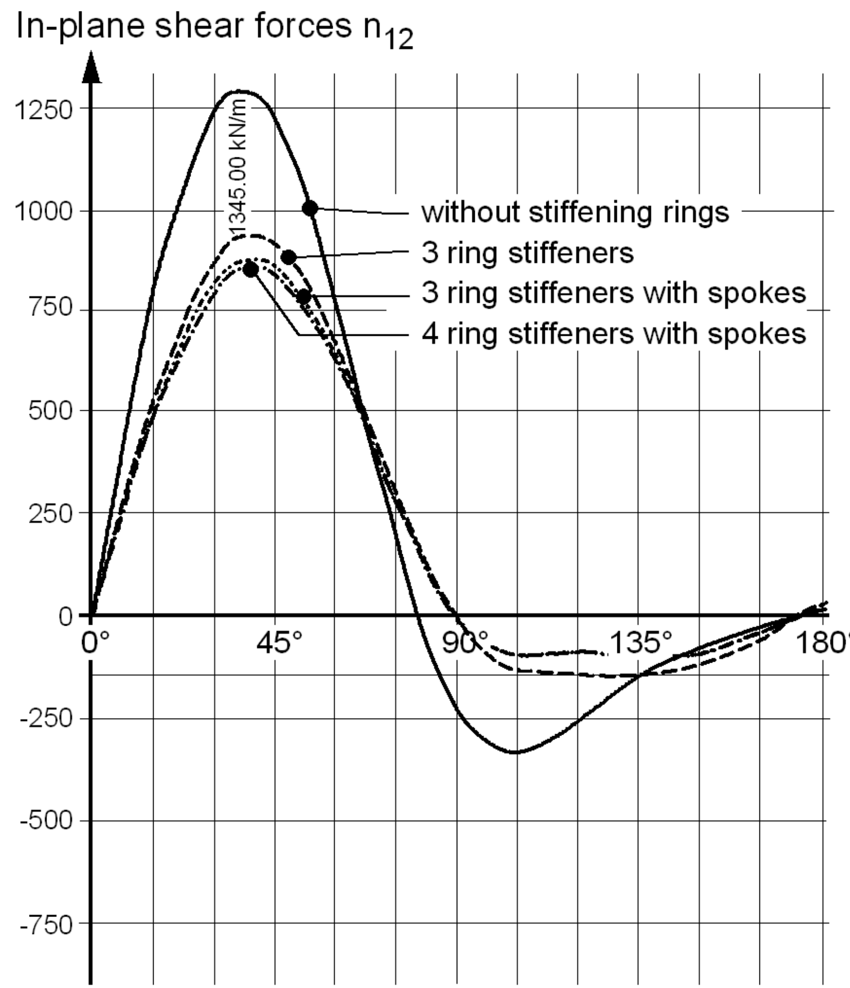
28 – 31 May 2008 • Cornell University, Ithaca, NY, USA

Small solar tower of 500m of height



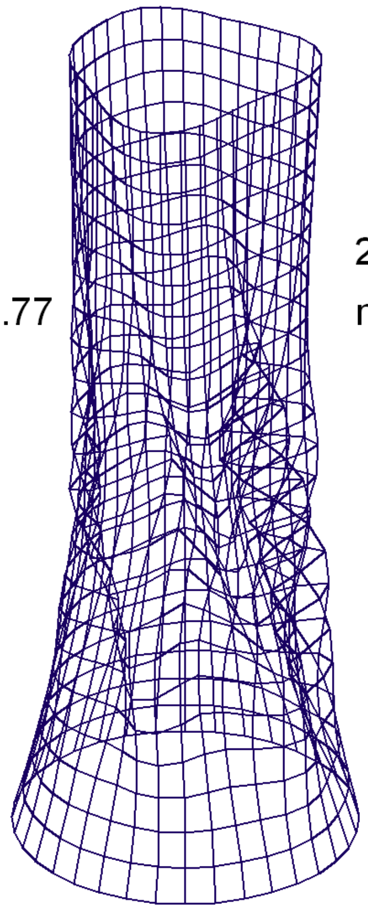
Meridional (n_{22w}) and in-plane shear (n_{12w}) forces, 500m tower



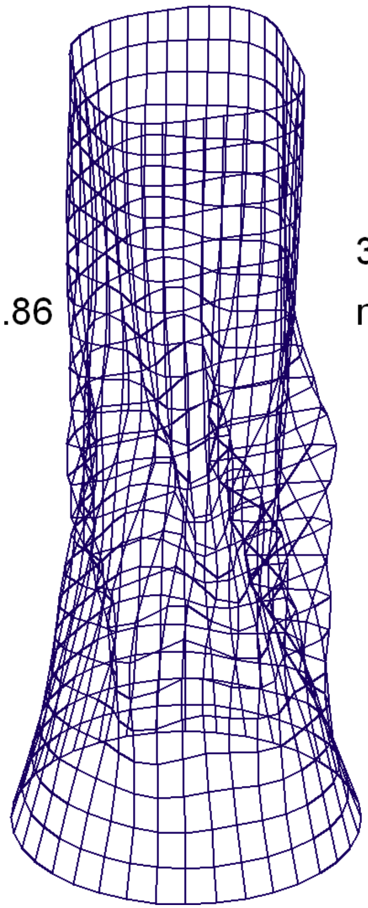


Instability modes: 500m tower without stiffenings rings (G+W+S)

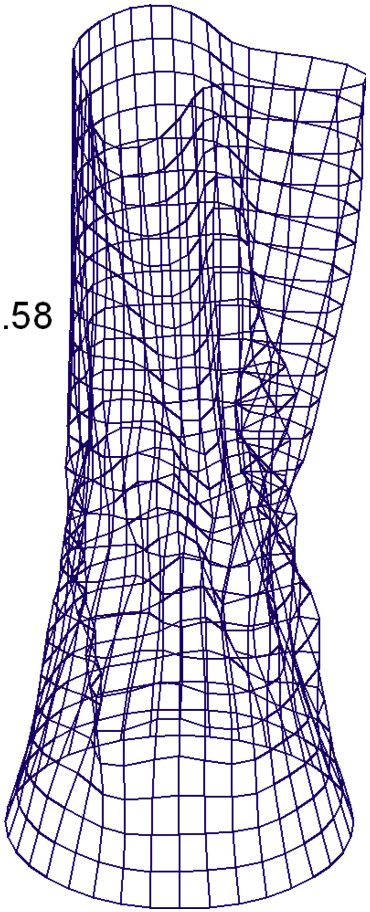
1st instability
mode: $\lambda_1 = 4.77$



2nd instabiliy
mode: $\lambda_2 = 4.86$

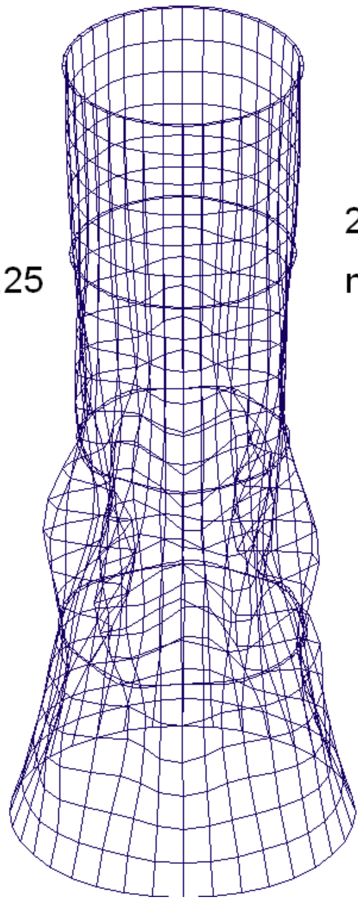


3rd instabiliy
mode: $\lambda_3 = 6.58$

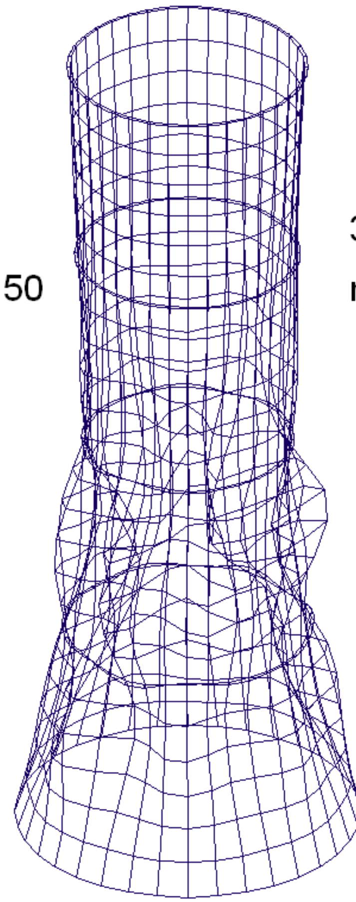


Instability modes for 500m tower with 4 stiffenings rings (G+W+S)

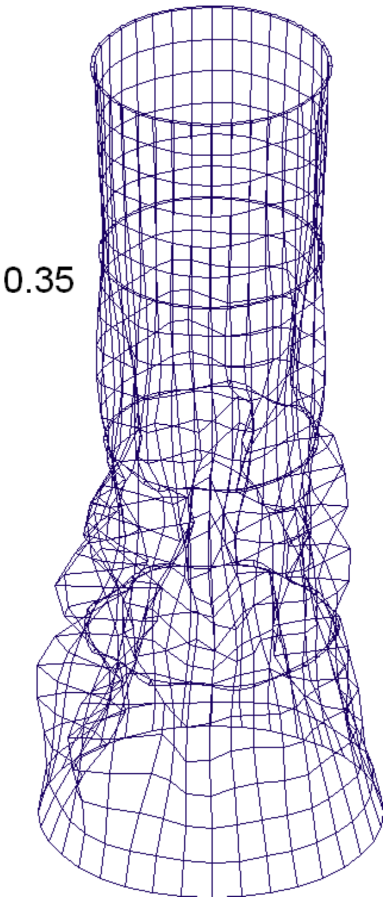
1st instability
mode: λ_1 = 8.25



2nd instabiliy
mode: λ_2 = 8.50



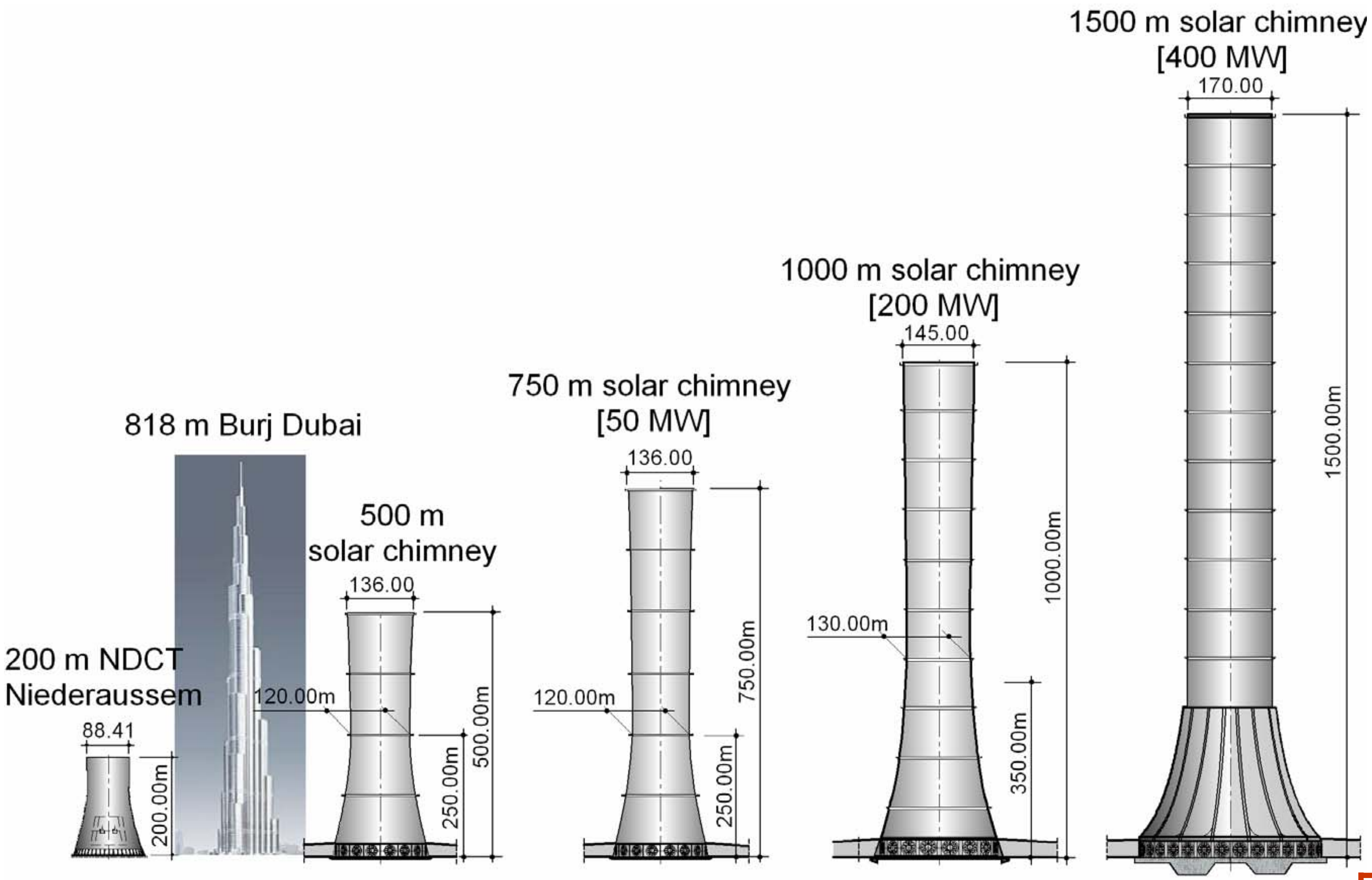
3rd instabiliy
mode: λ_3 = 10.35



Artist's view of large solar chimney power plant

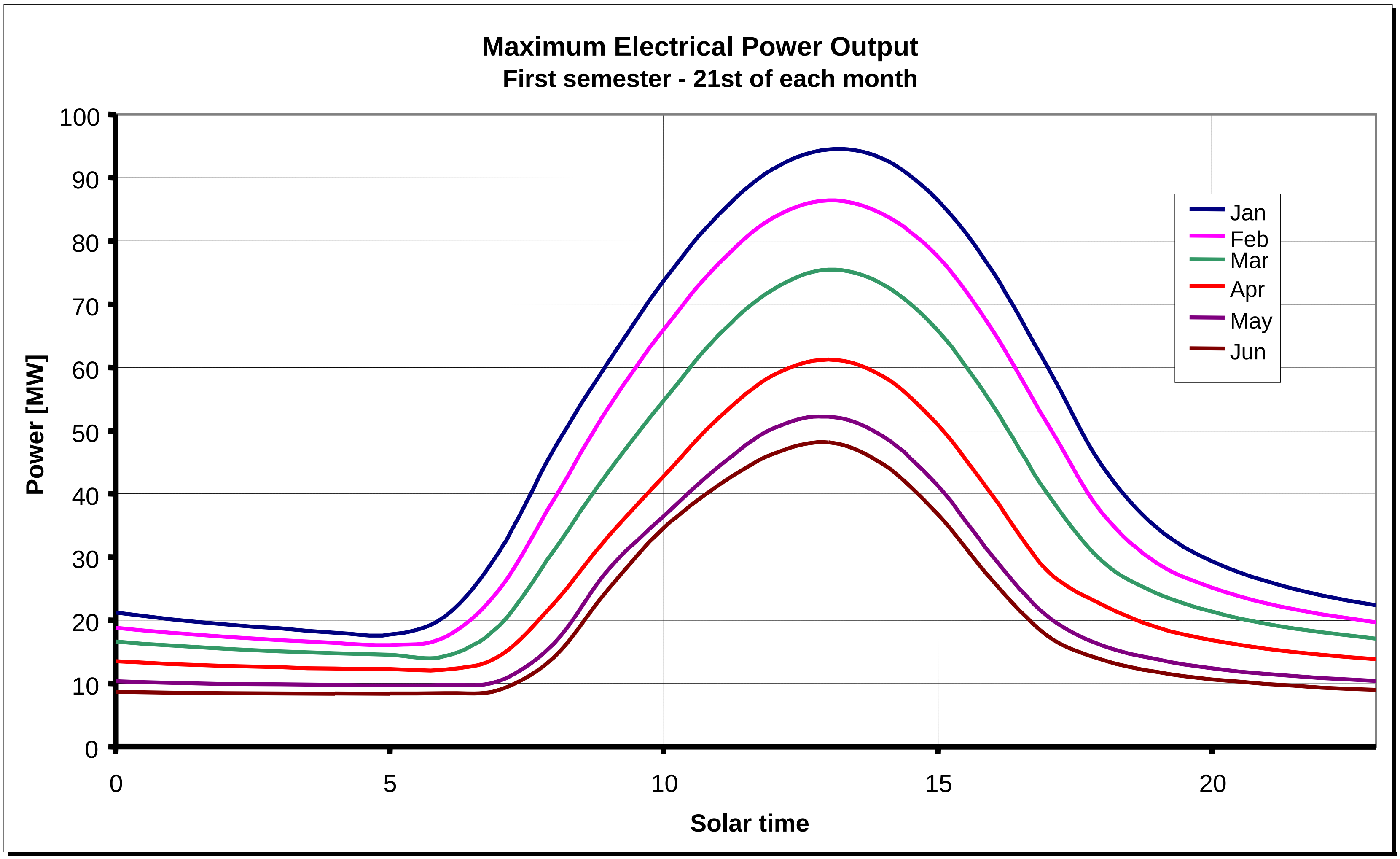
Acc. Stinnes (GreenTower Ltd.):
Short Executive Summary June 2007

From high natural draft cooling towers to solar chimneys



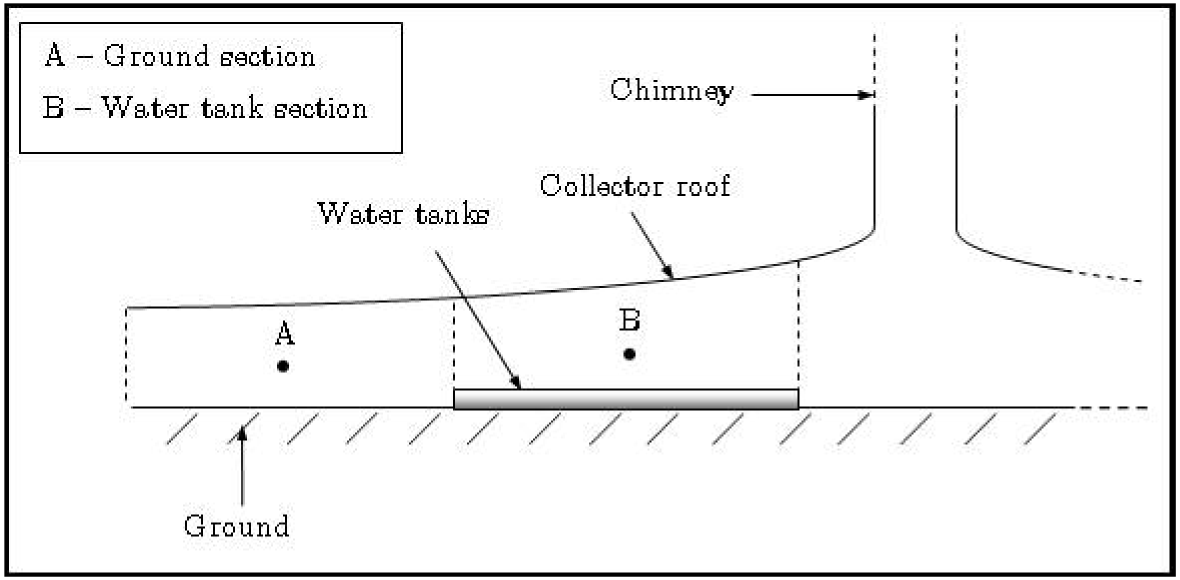
Results: Power output

Acc. Kroeger/Praetorius (Univ. Stellenbosch):
Solar Chimney Power Plant Performance



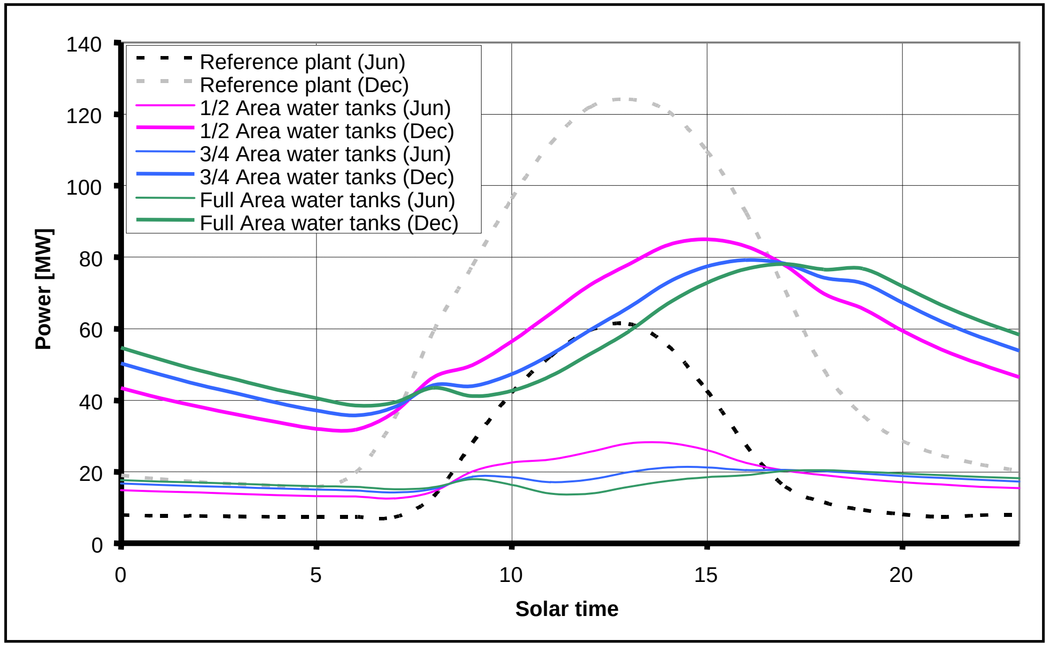
Regulating plant power output according to demand (cont.)

- 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.)

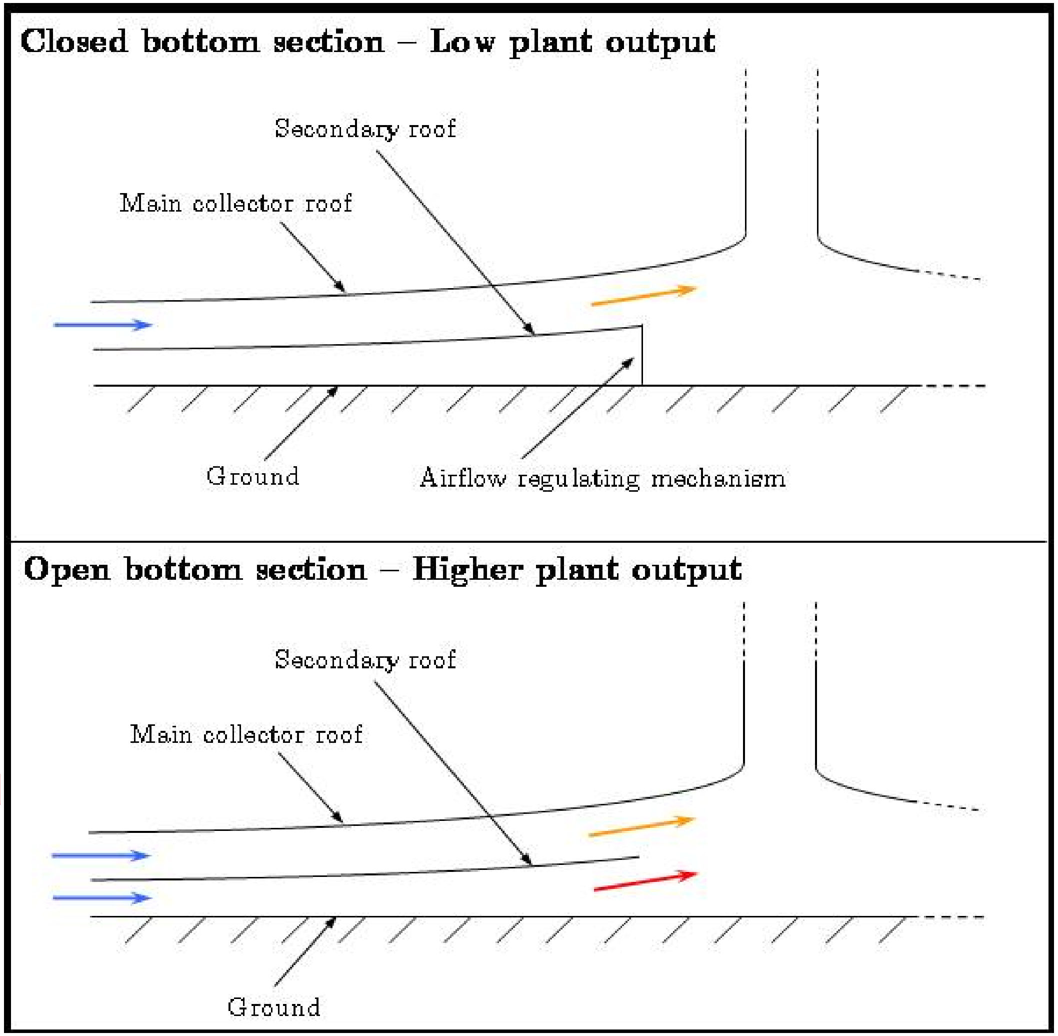
- Plastic covered water tanks
  - Partially covered collector area, constant tank depth
  - Significant static control
  - 2.4% (1/2 Area), 2.7% (3/4 Area), 2.6% (Full Area) reduction in annual power output



Acc. Kroeger/Praetorius (Univ. Stellenbosch):
Solar Chimney Power Plant Performance

Regulating plant power output according to demand (cont.)

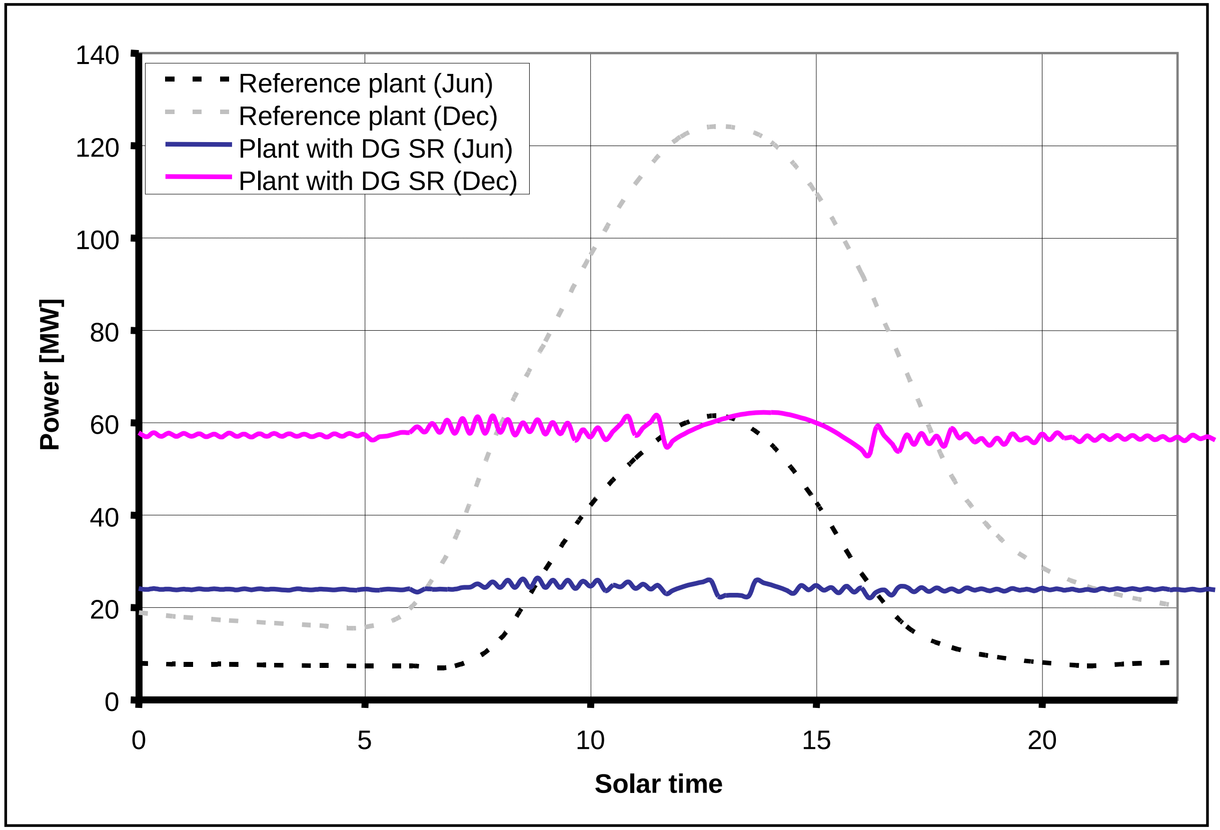
- Dynamic control
  - Base or peak power generation facility
  - Inclusion of additional collector roof
  - Inclusion of airflow regulating mechanisms
  - Plant given ability to store or release energy when needed
- Base load strategy
  - Keep power as constant as possible
- Peak load strategy
  - Maximum power delivered between 07:00 and 12:00 and 17:00 and 22:00 (Eskom)



Acc. Kroeger/Praetorius (Univ. Stellenbosch): Solar Chimney Power Plant Performance

Regulating plant power output according to demand (cont.)

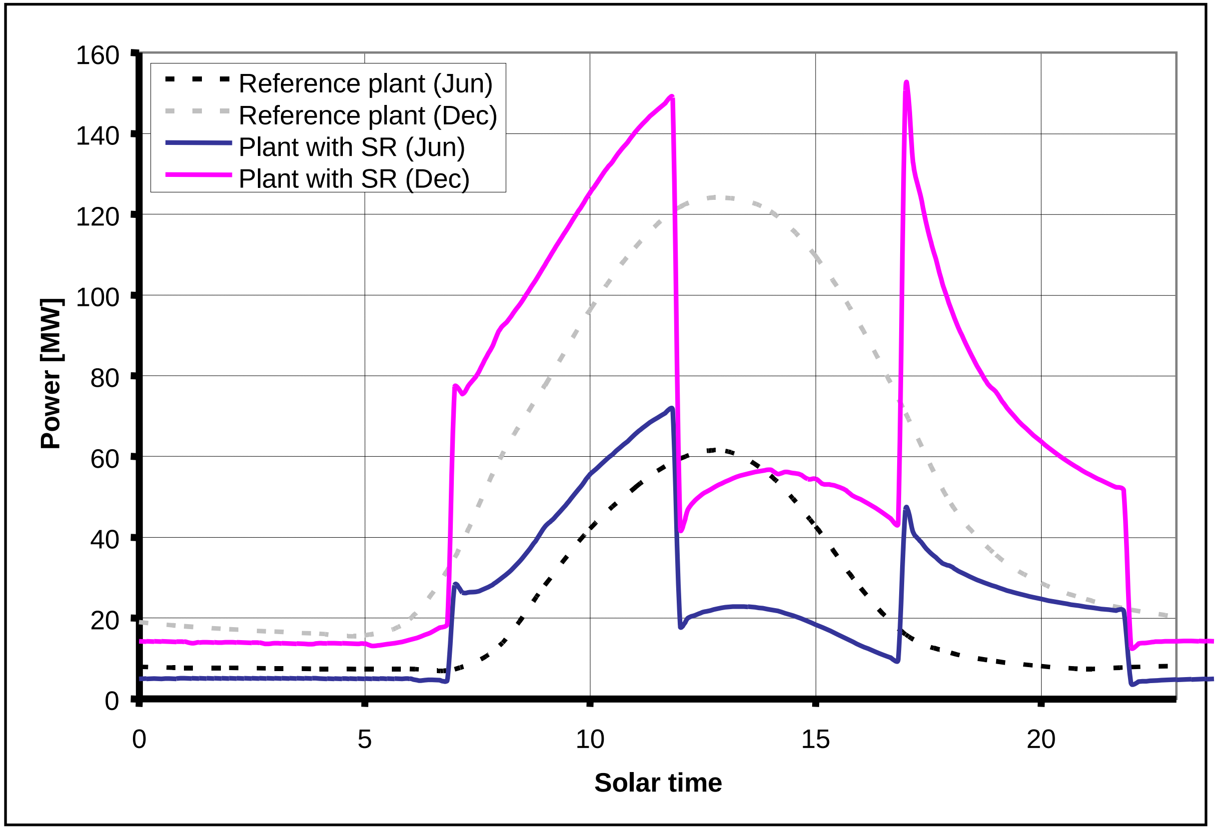
- Double glazed secondary collector roof
  - Base load: excellent control
  - 7.9% increase in annual power output



Acc. Kroeger/Praetorius (Univ. Stellenbosch): Solar Chimney Power Plant Performance

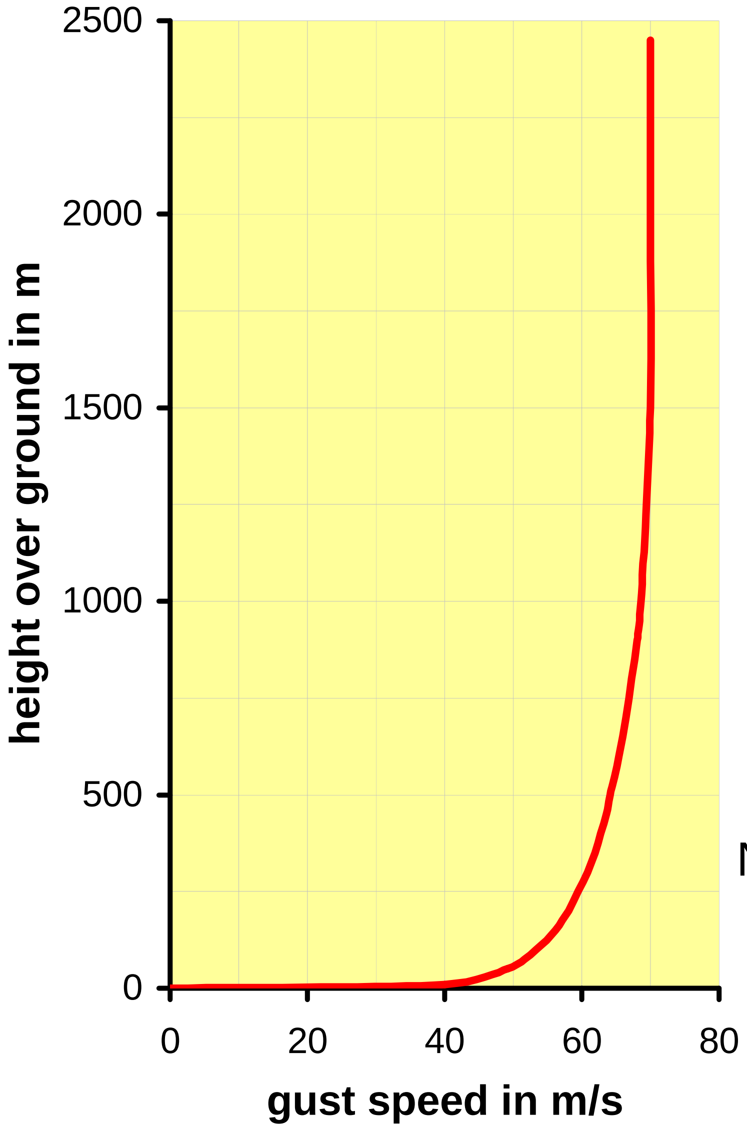
Regulating plant power output according to demand (cont.)

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



Acc. Kroeger/Praetorius (Univ. Stellenbosch):
Solar Chimney Power Plant Performance

Gust Wind Profile

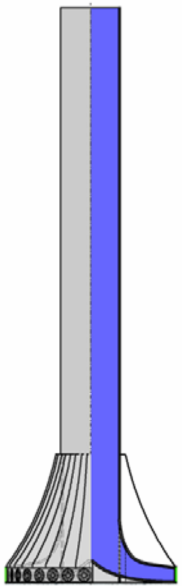


200m
Niederaußem

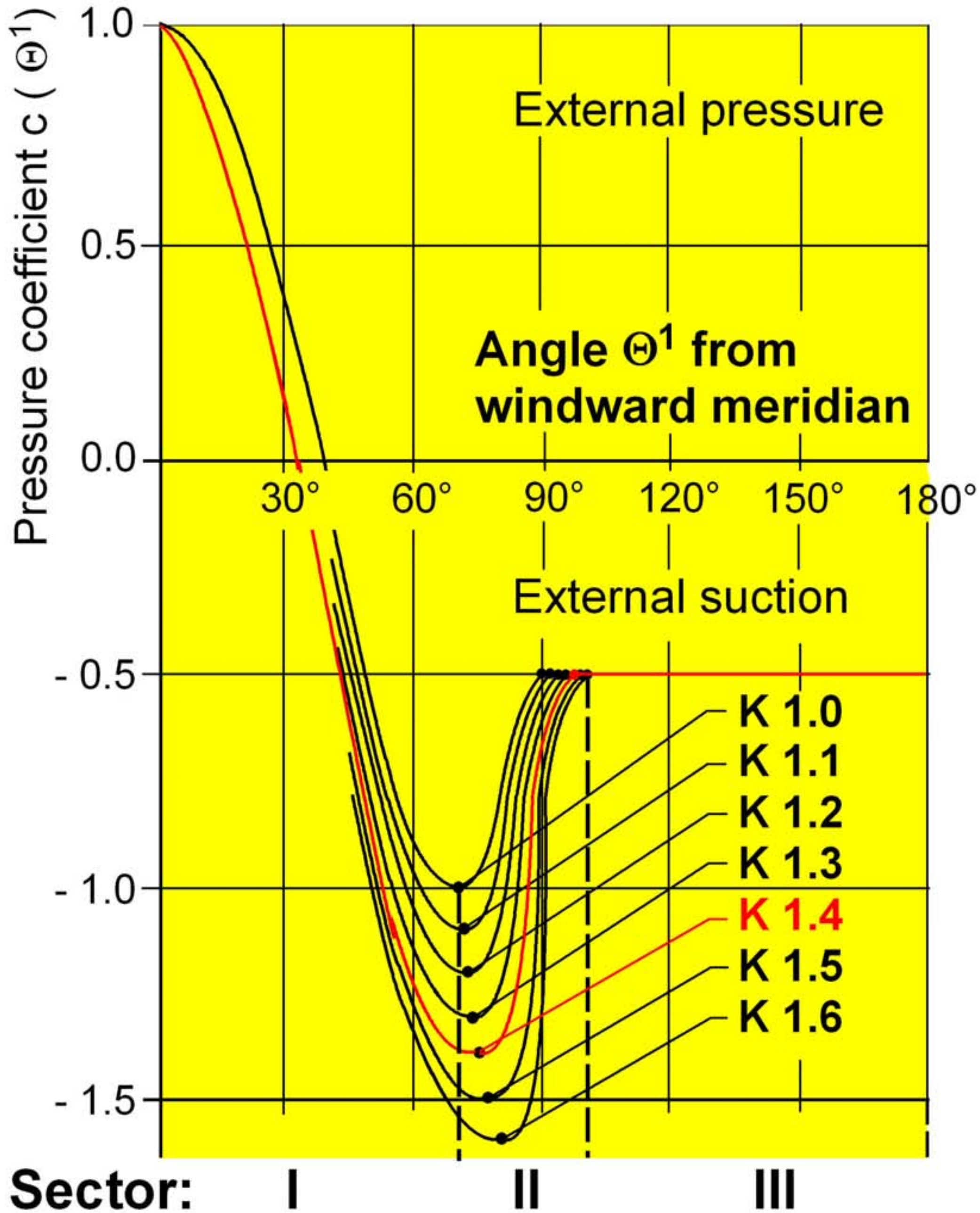
300m
Eiffelturm

800m
Burj Dubai

1500m
Green Tower



NDCT Niederaussem: Types of circumferential wind pressure distribution c (Θ^1)



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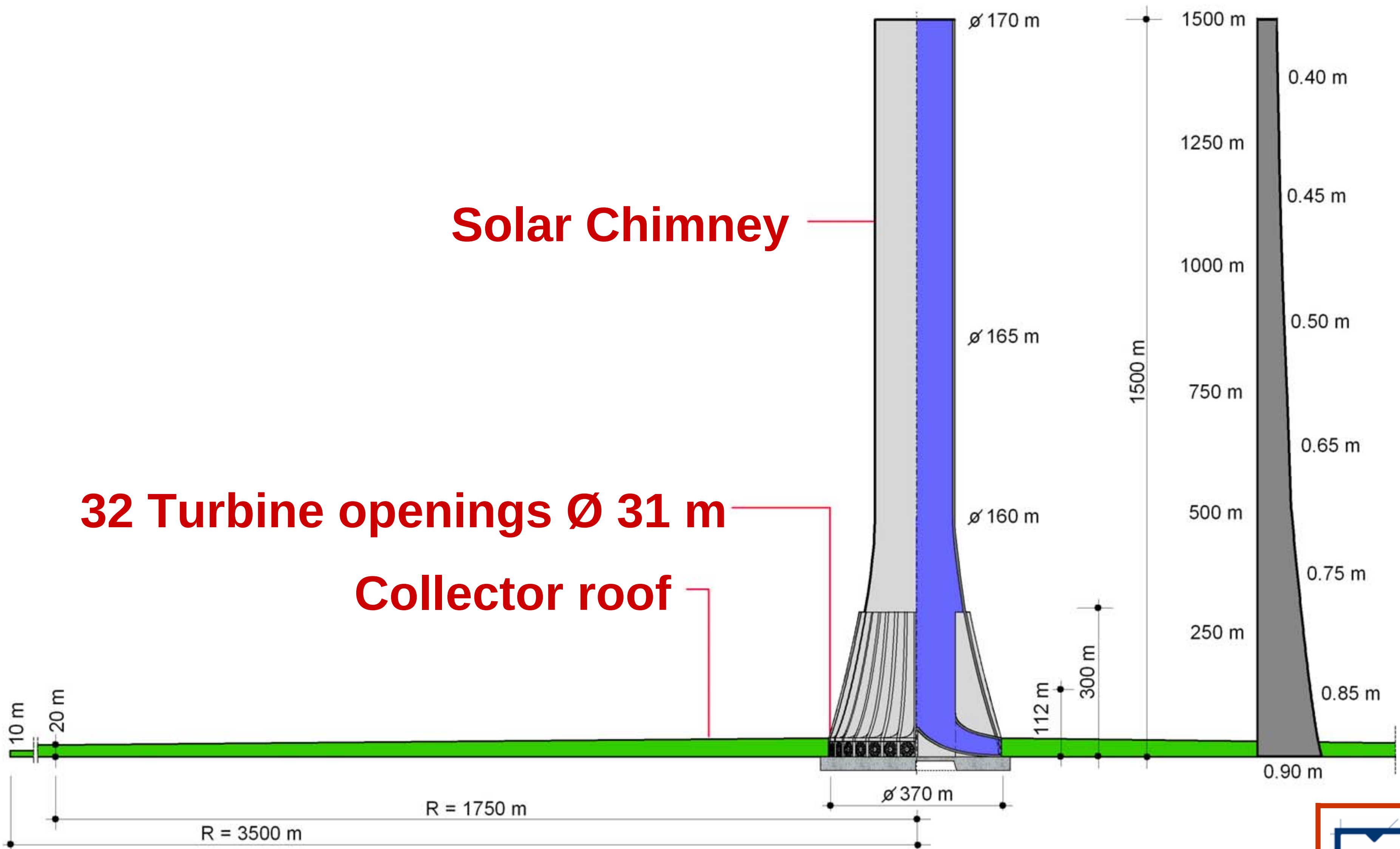
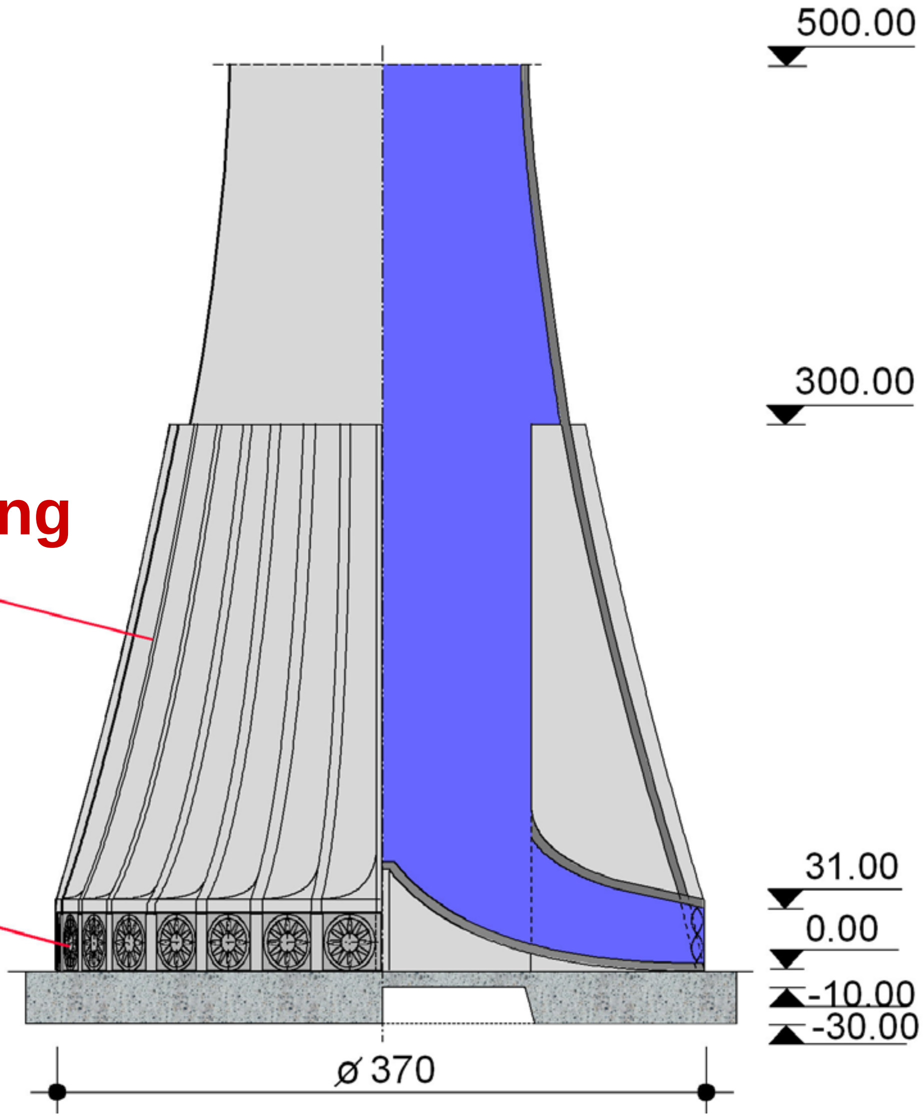
Green Tower Project Namibia



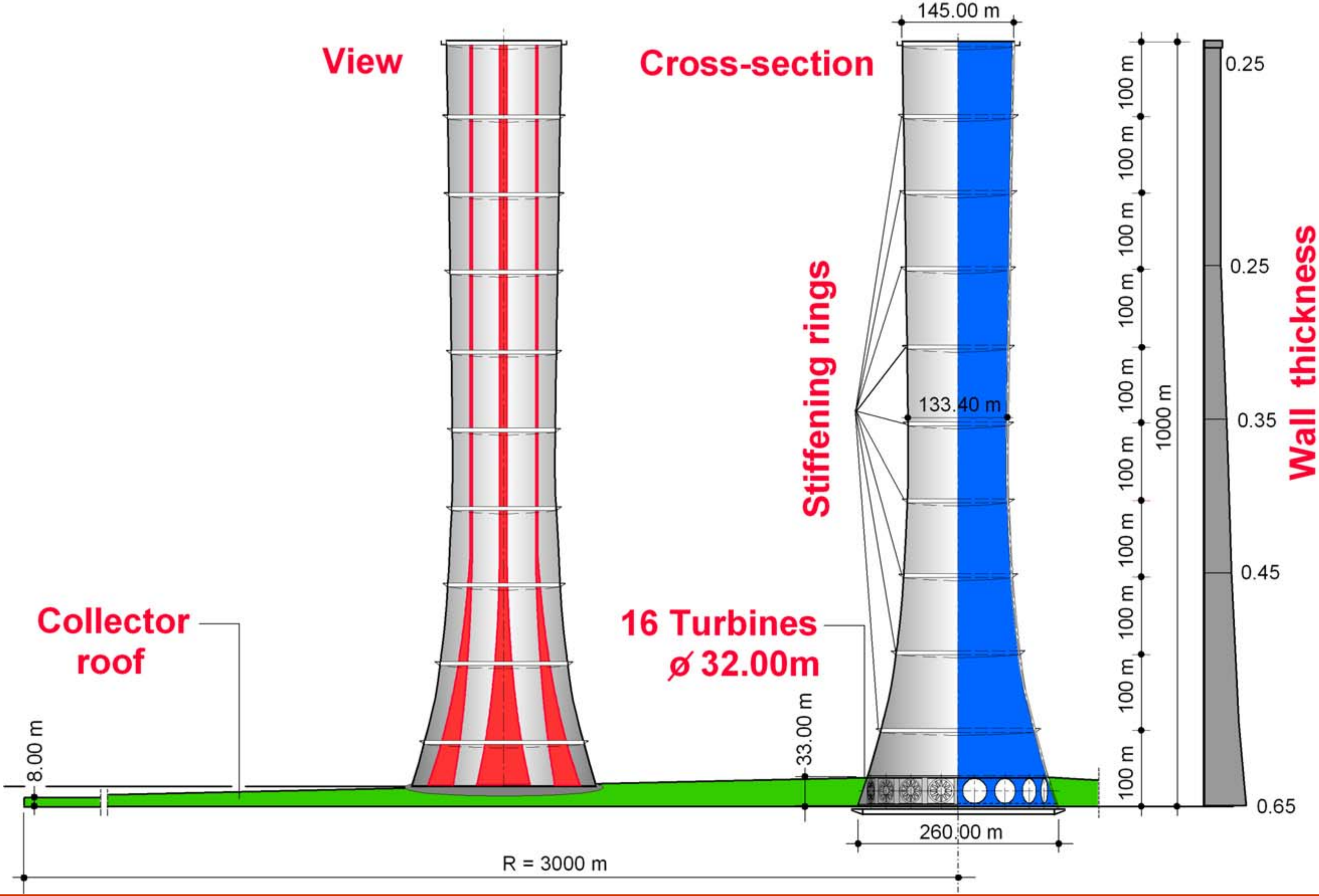
GreenTower Project Namibia: Tower foot alternative

32 Additional Stiffening Walls d = 2.0m

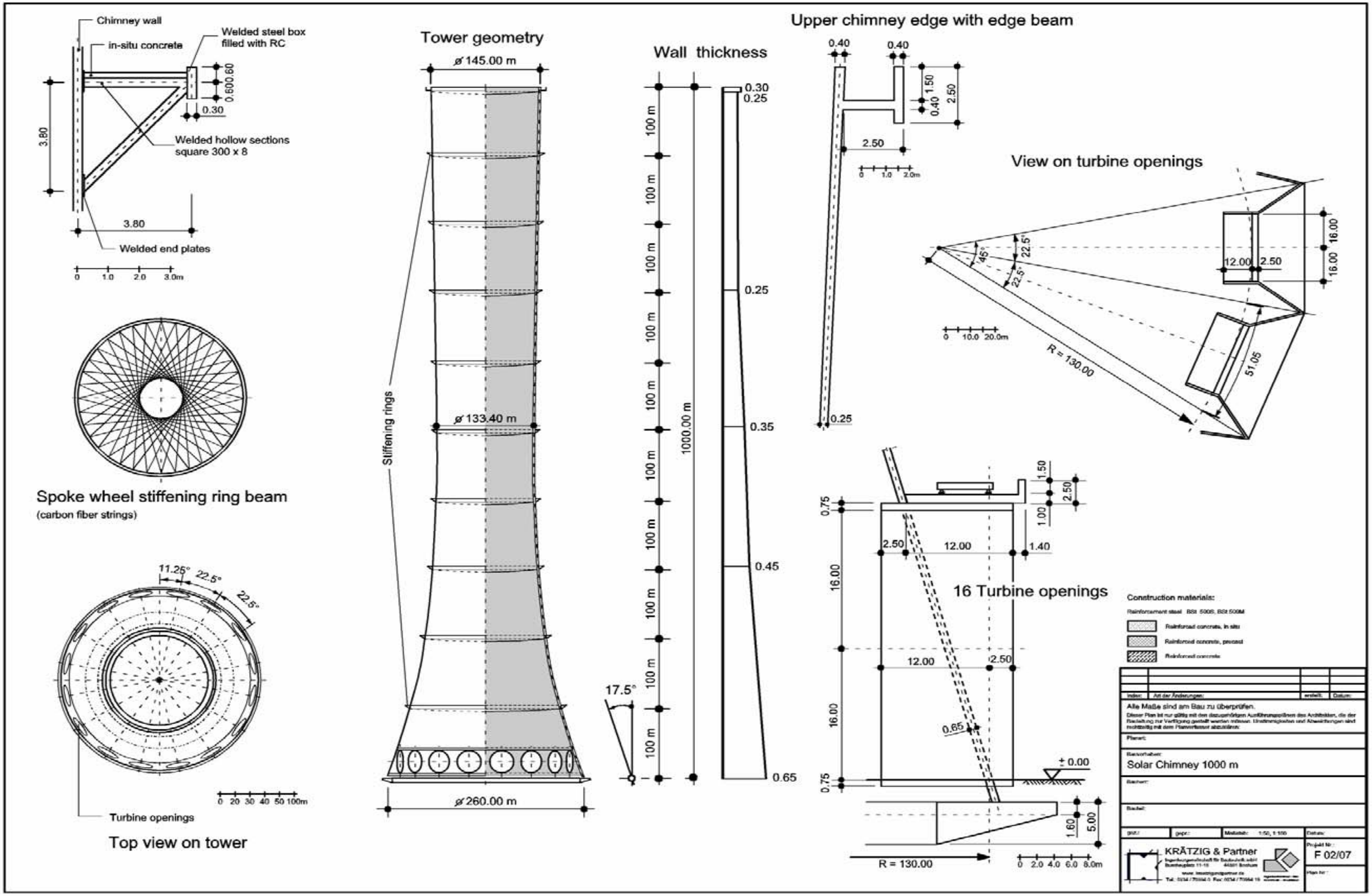
32 Turbines Ø 31 m



1000m tower for a 200MW SCPP



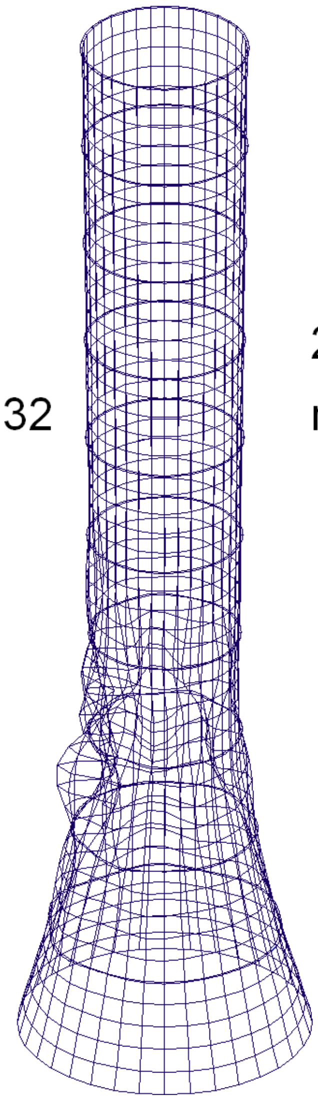
Solar Chimney Project Arabia: 1000m variant



Instability modes of 1000m tower for G+W+S

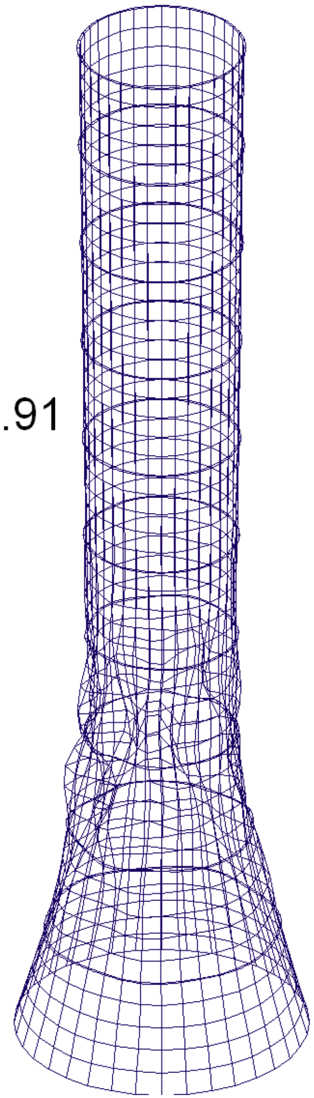
1st instability

mode: $\lambda_1 = 5.32$



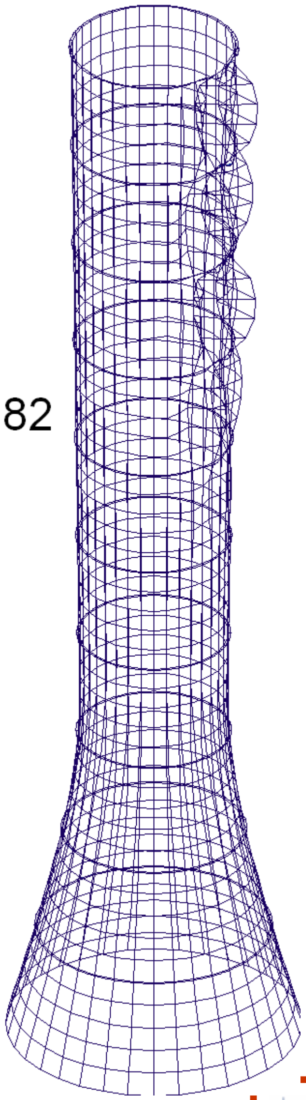
2nd instabiliy

mode: $\lambda_2 = 5.91$

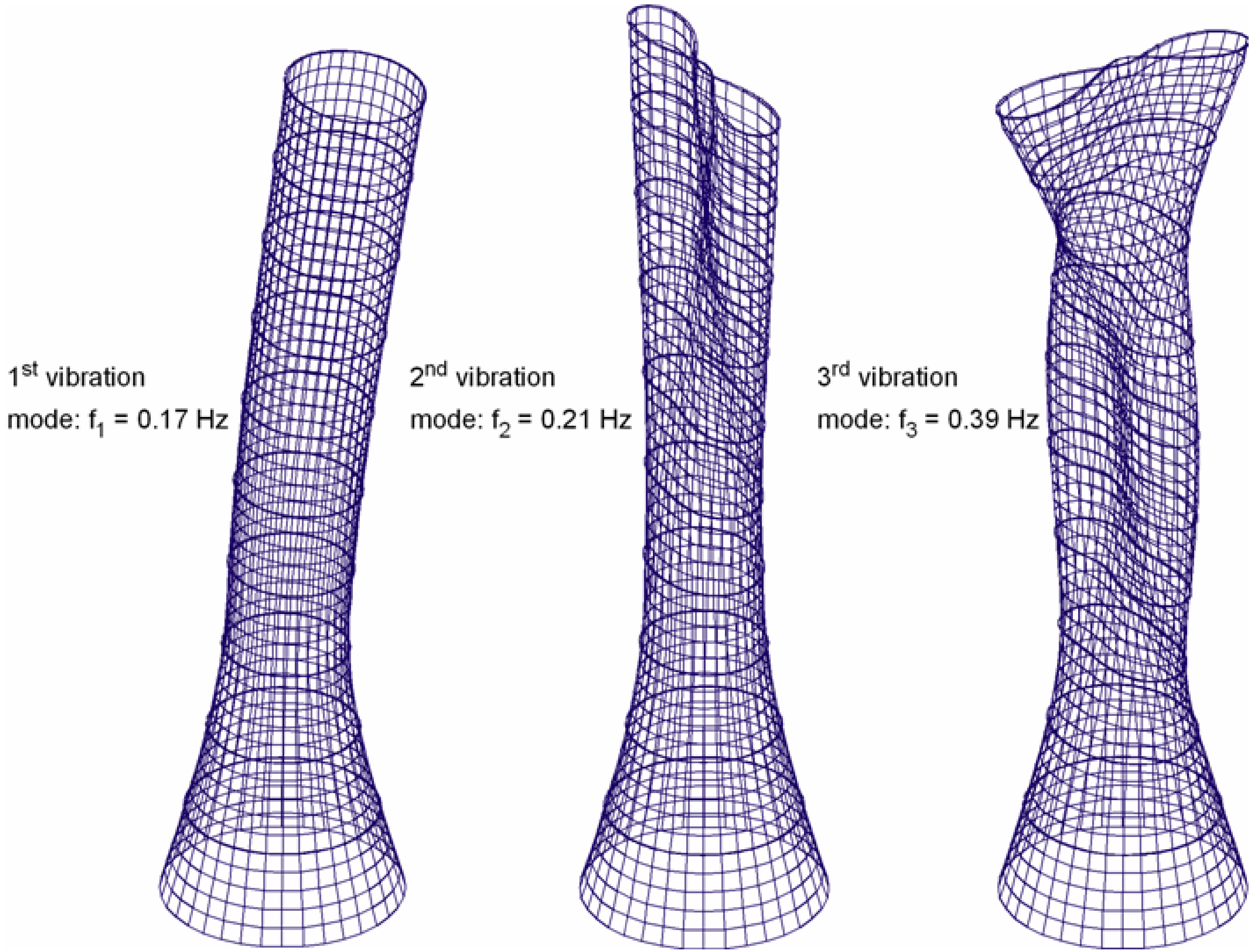


3rd instabiliy

mode: $\lambda_3 = 7.82$

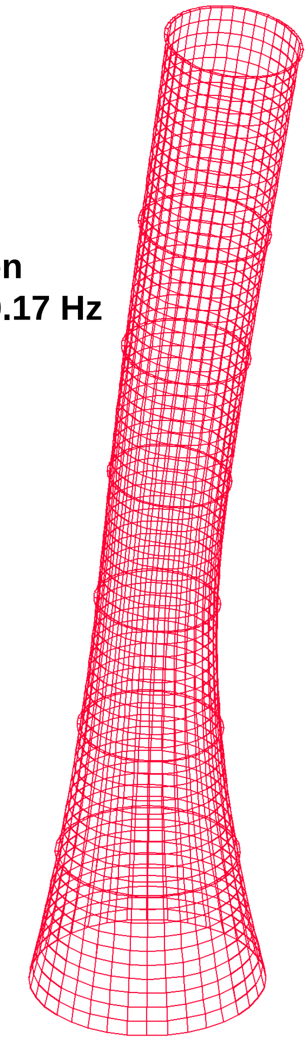


Vibration modes of 1000m tower

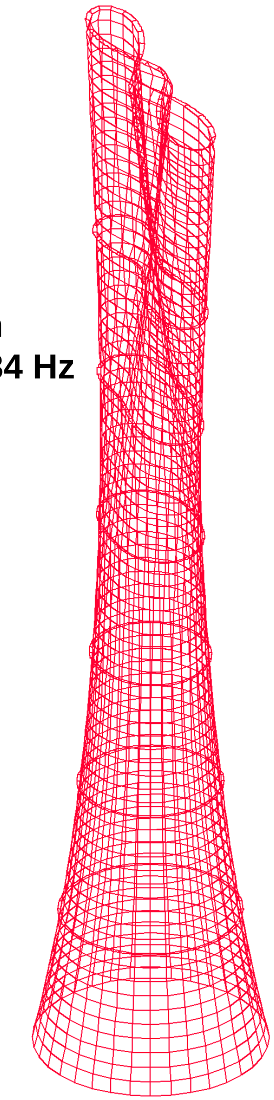


Vibration modes 1, 2 and 3 of 750m tower

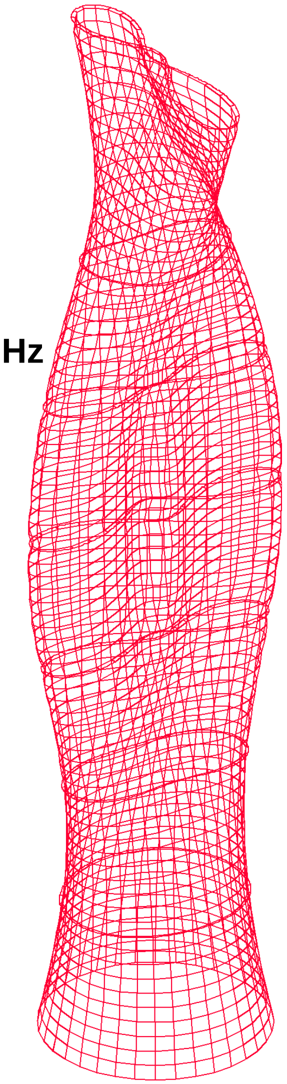
1st vibration mode f_1= 0.17 Hz



2nd vibration mode f_2= 0.34 Hz

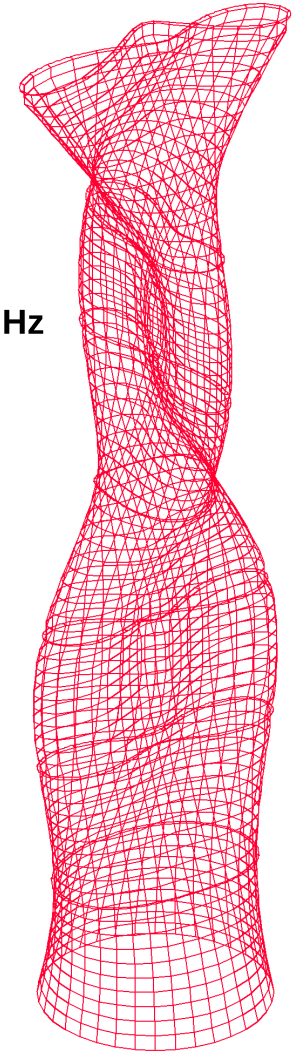


3rd vibration mode f_3= 0.50 Hz

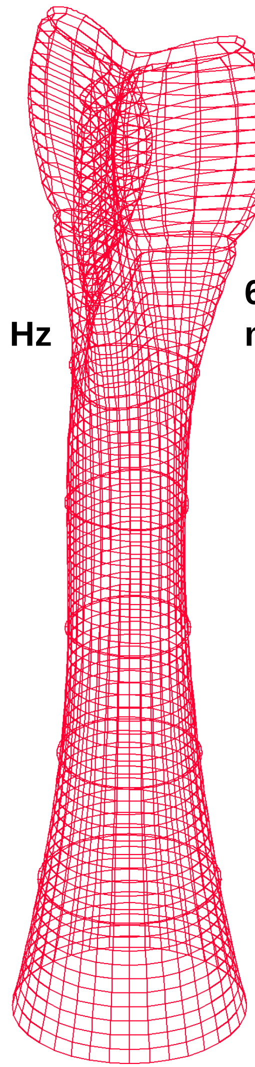


Vibration modes 4, 5 and 6 of 750m tower

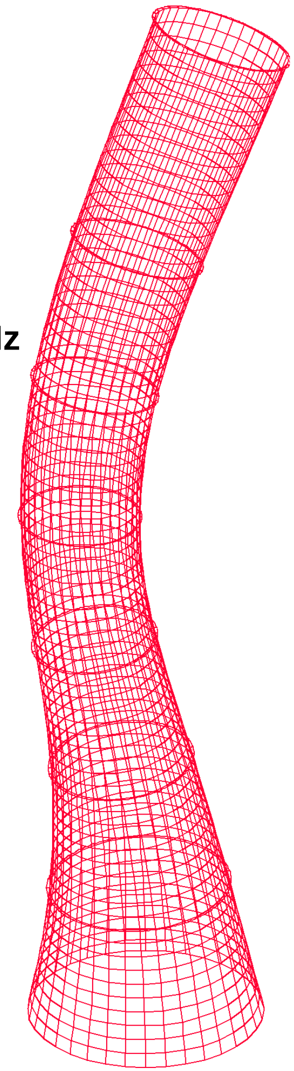
4th vibration
mode f_4= 0.77 Hz



5th vibration
mode f_5= 0.77 Hz



6th vibration
mode f_6= 0.84 Hz



Wilfried B. Krätzig, Reinhard Harte, Ralf Wörmann:

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4. **Conclusions:** When will SUPCs be improved structures like NDCTs?

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28 – 31 May 2008 • Cornell University, Ithaca, NY, USA