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CLOSE TO REALITY METHODS FOR THE STRUCTURAL DESIGN OF TOWERS
The basics of the relevant standards for industrial chimneys

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Abstract
Numerous large concrete chimneys were built in many different countries in the seventies and eighties last century. Unfortunately, the professional scene had to realize that those structures were very different in their forms, wall thicknesses and reinforcements. In addition to this many of them had been impaired by wide vertical through cracks decreasing their durability and wind bearing capacity. Both findings revealed dissatisfying situation that the existing chimney standards were mostly over safe and in some cases unsafe. Due to this, efforts were undertaken to develop modern, close to reality methods for the structural design of chimneys. These new design methods became popular and as such entered the most relevant European standards on chimneys.

Streszczenie
W latach siedemdziesiątych i osiemdziesiątych ubiegłego stulecia wzniesiono wiele wysokich kominów żelbetowych. Konstrukcje te różnią się między sobą kształtem, grubością ścian oraz zbrojeniem. Dodatkowo wiele z nich jest osłabionych rysami pionowymi o znacznej szerokości, co wpływa na zmniejszenie trwałości i nośności na działanie wiatru. Stwierdzić można, że wiele z istniejących kominów żelbetowych nie spełnia warunków bezpiecznego użytkowania. Konieczne więc było opracowanie nowoczesnych, zbliżonych do rzeczywistości metod projektowania kominów żelbetowych. Te nowe metody stały się popularne i jako takie zostały wprowadzone do wielu stosownych europejskich norm projektowania.

Keywords: **Reinforced concrete structures; Industrial chimneys; Deformation behavior; Moments of 2nd order; Crack width; Tower design; Deformation laws; Constraint; Non linear analysis.**

1. PAPER BACKGROUND

1.1. Situation

After recognizing deficiencies in the structural design of chimneys, CICIND (International Chimney Association) decided to produce own model code [02] containing close to reality methods to design chimneys safely and economically in a consistent manner. Among others, the guideline should offer solutions to the following issues absorbing the professional scene for years:

- Difference between the local design regarding bearing capacity and the global design regarding deflections
- Relevance of moments of 2nd order and their close to reality determination
- Impact of temperature on activation of moments particularly with simultaneous wind action
- Prevention of loss of the wind bearing capacity caused by wide vertical through cracks
- Increase of durability by effective limitation of crack widths

1.2. Design Methods

Appropriate research efforts have resulted in development of several design methods [1, 7 to 13] which have been widely accepted in standards [2, 3, 4, 27], research [5, 6, 14, 15, 24, 28] and design practice [16 to 22, 25, 26]. The design methods described in this paper apply for the prediction of the following aspects of the structure behavior:

Vertical load bearing capacity

Deflections of the entire tower to determine moments of 2[nd] order

Strains in the individual horizontal cross sections to prevent collapse

Horizontal load bearing capacity

Steel stress in the individual vertical cross sections to prevent yielding and formation of through carcks

Widths of the vertical cracks to assure proper durability of painting and ring reinforcement

1.3. New Standards

The new design methods described in this paper became popular and as such entered the following relevant standards:

CICIND Model Code for Concrete Chimneys with Commentaries, Part A: The Shell, October 1984 [02]

DIN 1056 Commentary: Industrial Chimneys in Solid Construction, by Nieser & Engel, 1986 [7]

CICIND Model Code for Concrete Chimneys with Commentaries, Part A: The Shell, August 2001 [2]

DIN EN 13084-2: Free-standing Chimneys, Part 2: Concrete Chimneys, January 2006 [4]

DIN V 1056: Free-standing Stacks in Solid Construction, Calculation and Design, Draft March 2006 [3]

PNB EN 13084-2: Free standing chimneys, Part 2: Concrete Chimneys, January 2006 [27]

2. VERTICAL LOAD BEARING CAPACITY

2.1. Design Process

Design process of the vertical load bearing capacity consists in limitation of concrete strains ε_c activated by wind and dead load actions. This is assured by a proper design that provides shell diameters D, wall thicknesses h and ratios of vertical reinforcement ρ_v. Such a design process [10, 13, 21] comprises 5 Steps:

(0) Model structure by subdivision into elements through nodal points

(1) Assign values D, h, ρ_v and corresponding deformation laws M - k to each node

(2) Compute normal forces from weight and bending moments from wind M

(3) Determine deflection and the corresponding moments of 2[nd] order ΔM until convergence (no increase in δ)

(4) Compute strains ε on the basis of equilibrium of internal and external forces to assess the strength

(5) Repeat Steps (1) to (4) in case of insufficient (too high or to low) concrete strains

2.2. Structure Modeling

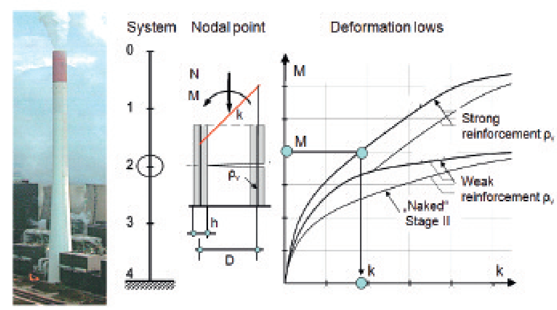

Figure 1.

Structure modeling [10, 13, 21] includes the following measures:

- Formation of a numerical computation system by use of nodal points which describe average post cracking deformation behavior by means of deformation laws.
- Assignment of non-linear deformation laws which demonstrate individual structure states

  Primary high stiffness of the "virgin", not cracked node

  Initial cracking characterized by individual cracks, located far from each other

  Final cracking arising from many cracks with crossover of the adjacent transition areas

  Yielding of reinforcement at cracks

2.3. Moments of 2[nd] Order

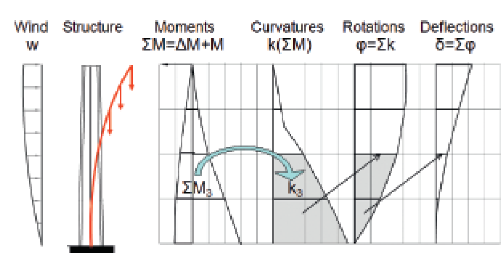

Figure 2.

Moments of 2nd order [10, 13, 21] are determined by double integration of curvatures gained from the deformation laws:

- Moments from wind M and moments of 2nd order at the individual nodes
- Curvatures k(M+ΔM) extracted from the corresponding deformation lows
- Rotations $\varphi = \Sigma k$ as numerical integration of curvatures
- Deflections $\delta = \Sigma\varphi = \Sigma\Sigma k$ as numerical integration of rotations
- Moments of 2nd order ΔM from deflections

By use of this close to reality numeric procedure the following simplification [8] was developed for the CICIND Model Code [2] for quick use in practice:

$\Delta M(z) = (1 + 2.3\ z/H)\ (1 - z/H)^{2..3}\ (75 - 0.12\ H)\ (1 + \sigma/6)\ H^2/100\ (M_w(0)\ N_D(0)/(E_c\ I(0))$

$M_w(0)$	moment from wind at the tower bottom [MNm]
$\Delta M(z)$	moment of 2nd order at any elevation z [MNm]
$N_D(0)$	normal force at the tower bottom [MN]
H	tower height [m]
E_c	modulus of elasticity of concrete [MNm²]
I(0)	moment of inertia at the tower bottom [m⁴]
ρ	reinforcement ratio [%]

2.4. Design Example

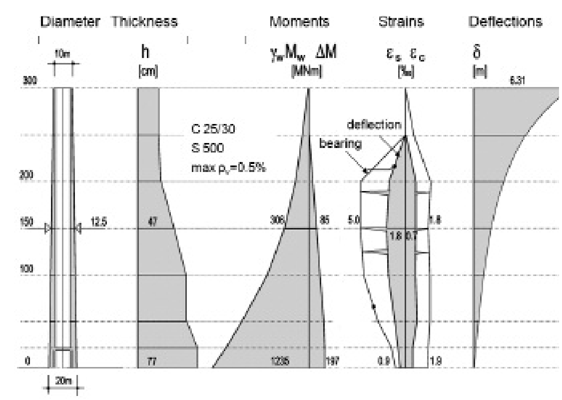

Figure 3.

Above methods were used to design windshield of a large chimney. Since the ultimate strains are widely utilized, the structural design is both safe and economic:

		bottom	top
Diameter	D	20.00 m	10.00 m
Wall thickeness	h	0.77 m	0.30 m
Vertical reinforcement	ρ_v	0.50 %	0.35 %
Concrete strain	ε_c	1.90 ‰	<2.00 ‰
Deflection	δ		6.31 m

3. HORIZONTAL LOAD BEARING CAPACITY

3.1. Design Process

Design process of the horizontal load bearing capacity consists in limitation of steel stresses ss and crack widths wk activated by temperature and wind actions. This is assured by a proper design that provides circumferential reinforcement ρh and bar diameters ds. Such a design process [09, 10, 13, 21] comprises 5 Steps:

(0) Model the considered cross section by means of a closed ring

(1) Assign values ρ_v, d_s and corresponding deformation laws M - k

(2) Determine cracking moment M_{cr} from the tensile strength of concrete

(3) Compute steel stress σ_s from the cracking moment

(4) Compute crack width w_k from the cracking moment

(5) Repeat Steps (1) to (4) in case of insufficient (too high or to low) steel stresses or crack widths

3.2. Structure Modeling

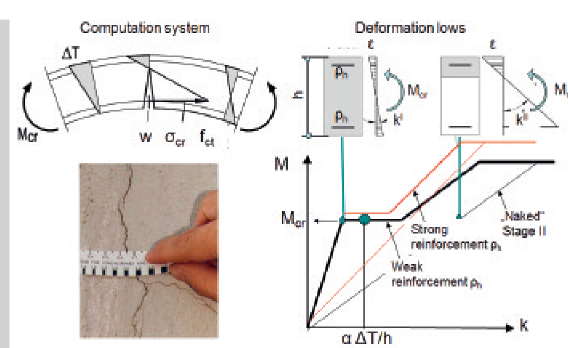

Figure 4.

Structure modeling [9, 10, 13, 21] includes the following measures:

- Formation of a numerical computation system by one nodal point describing the ring behavior
- Assignment of polygon like deformation laws which demonstrate the individual structure states

  Primary high stiffness of not cracked node (strongly rising section)

  Initial cracking characterized by individual cracks, located far from each other (horizontal section)

  Final cracking arising from many cracks with crossover of the transition areas (rising section)

  Yielding of reinforcement at cracks (horizontal section)

By such polygon like deformation laws, the following rules [9, 10, 13, 21] for behavior of chimney cross sections under temperature are valid:

(1) Validity of the cracking moment for the design

$M_{cr} \approx f_{ct}\, h^2/6$

(2) Independence of the cracking temperature ΔT_{cr} of concrete strength f_c

$k_T = k_M \Rightarrow \alpha_T\, \Delta T_{cr}/h = 2\, f_{ct}/(E_c\, h) \Rightarrow$
$\Delta T_{cr} = 2\, f_{ct}/(\alpha_T\, E_c)$

(3) Dependence of the steel stress σ_{cr} of tensile strength of concrete f_{ct}

$$M^I = M^{II} \Rightarrow f_{ct}\, h^2/6 \approx \sigma_{cr}\, A_s\, 0.8\, h \Rightarrow \sigma_{cr} = 0.2\, f_{ct}/\rho$$

3.3. Crack width

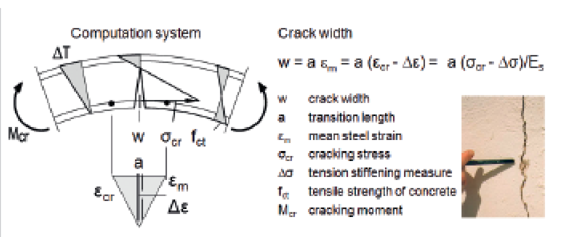

Figure 5.

Crack width results from the steel slip within the transfer length and obeys the following relation [09, 10]:

$w = a\, \varepsilon_m = a\, (\varepsilon_{cr} - \Delta\varepsilon) = a\, (\sigma_{cr} - D\sigma)/E_s$

w crack width

a transfer length needed to induce steel stress into concrete in which steel slip against concrete occurs

ε_{cr} strain peak value at the very crack

ε_m middle strain expressed by the difference between ε_{cr} and the tensile stiffening effect $\Delta\sigma$

By use of this design method, the following equation was developed [9, 10] for use in practice:

$w_k = 3.5\, (\sigma_{sr}^{0.88}\, d_s/f_{cm}^{0.66})^{0.89}\, (\sigma_s - 0.4\, \sigma_{sr})/E_s$

σ_{sr} crack stress [MN/m²]

σ_s acting steel stress [MN/m²]

E_s modulus of elasticity of steel [MN/m²]

d_s bar diameter [mm]

f_{cm} mean concrete strength [MN/m²]

3.4. Design Example

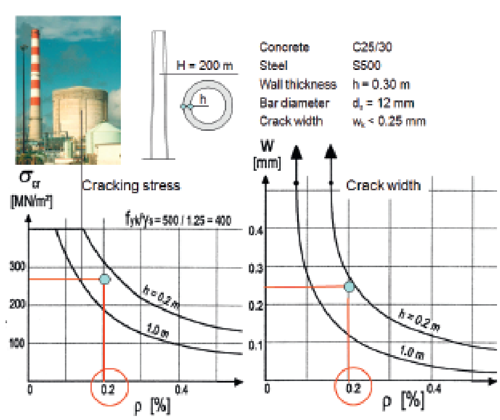

Figure 6.

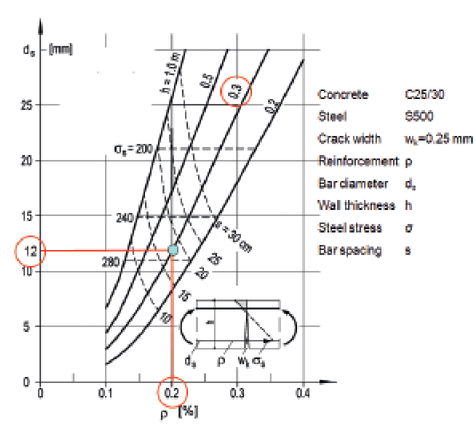

Figure 7.

Above methods were used to design windshield of a large chimney. Since the allowable values are widely utilized, the structural design is both safe and economic:

Wall thickness	h	0.30 cm	
Ring reinforcement	ρ_h	0.20 %	
Bar diameter	d_s	12 mm	
Steel stress	σ_s	270 MN/m^2	<300 MN/m^2
Crack width	w	0.25 mm	<0.30 mm
Bar spacing	s	17.5 cm	< 30.0 cm

The same results are provided as one of the design charts [7, 9, 10] developed for the CICIND Model Code [2] for quick use in practice.

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