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Design Wind Loads for Concrete Chimneys - A Comparison Between ACI 307-08 and NBR 6123:1988 Standards

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Abstract

Concrete chimneys are one of the main components of termal power plants. In design of industrial concrete chimneys the structural integrity is characterized by the ultimate limit resistance against wind action and the serviceability limit resistance against constraints caused by thermal effects.
Currently the design of concrete chimneys is regulated in codes such as the international CICIND Model code for concrete chimneys, the CEN - Eurocode EN 13084-2, the ACI 307-08 and ABNT NBR 6123:1988.
Currently the design of concrete chimneys is regulated in codes such as the international DIN 1056-2005 code, CICIND Model code, the CEN - Eurocode EN 13084-2 and the ACI 307-08 – code requirements for reinforced concrete chimneys from the American Concrete Institute. All codes have in common that the design of the chimney is performed via beam theory methods.
Reinforced concrete chimneys shall be designed to resist the wind forces in both the along-wind and across-wind directions. In addition, the hollow circular cross section shall be designed to resist the loads caused by the circumferential pressure distribution.
Along wind speed can be expressed as a time function composed of a mean and a floating components based on the classical DAVENPORT (1967) approach. It amplifies the mean wind force applying the gust response factor G_f.
This article is based on the wind design loads according to ACI 307-08 and ASCE 07-05 standards and also performing some numerical comparisons with the NBR 6123:1988 Brazilian wind load.
The formulation proposed is applied to a 180-meter-high concrete chimney and the results are compared with those obtained through the recommendation given in the standard ABNT NBR 6123:1988 for the discrete modal wind dynamic analysis.

Key-words
Wind load analysis; concrete chinmeys; ACI 308-08 and NBR 6123:1988 wind load standards; discrete modal wind dynamic analysis.

Introduction

Although the effects of natural wind on structures are in general of a dynamic nature, not all structures react with pronounced vibrational behaviour, that are the mass-inertia forces and the damping forces do not represent a significant role.
A structure can be considered either rigid (negligible dynamic effects) or flexible (dynamic effects is considered). BACHMANN *et Al.* (1995) states that a structure subjected to wind is defined as rigid whether the dynamic response of gusts or turbulence effects does not exceed 10% of the corresponding static response.
The design of concrete chimneys is regulated in codes such as the international CICIND (2011), DIN 1056, the CEN - Eurocode EN 13084-2, ACI 307-08 and ABNT NBR 6123:1988. All codes have in common that the design of the chimney is performed via beam theory methods.

KARACA AND TÜRKELI (2012) have used several international standards for the determination and comparison of wind loads applied to industrial reinforced concrete chimneys.
Assuming that the mean velocity of the wind remains constant over a representative time interval, the effects on the structure are purely static (mean response). Speed fluctuations can produce, in flexible structures, important oscillations towards the mean velocity (resonant response).
In the design practice, structures submitted to wind are evaluated through static analyses with equivalent loads, where the influence of the resonant response is taken into account by the gust response factor, proposed by DAVENPORT (1967).
Structures with frequencies lower than this value, mainly weakly damped, may present an importante resonant response and must have their dynamic properties considered in the structural analysis. The Brazilian standard ABNT NBR 6123:1988 considers the gust factor method for buildings and chimneys with a natural period equal or greater than 1 second, where the discrete model is applied in buildings with variable properties and is considered in this work.
According to ACI 307-08 standard, reinforced concrete chimneys shall be designed to resist the wind forces in both the along-wind and across-wind directions. In addition, the hollow circular cross section shall be designed to resist the loads caused by the circumferential pressure distribution.
Numerical results for a 180-meter-high concrete chimney example, according to ACI 307-08 and NBR 6123:1988 standards, are presented.

Wind loads calculation according to ACI 307-08

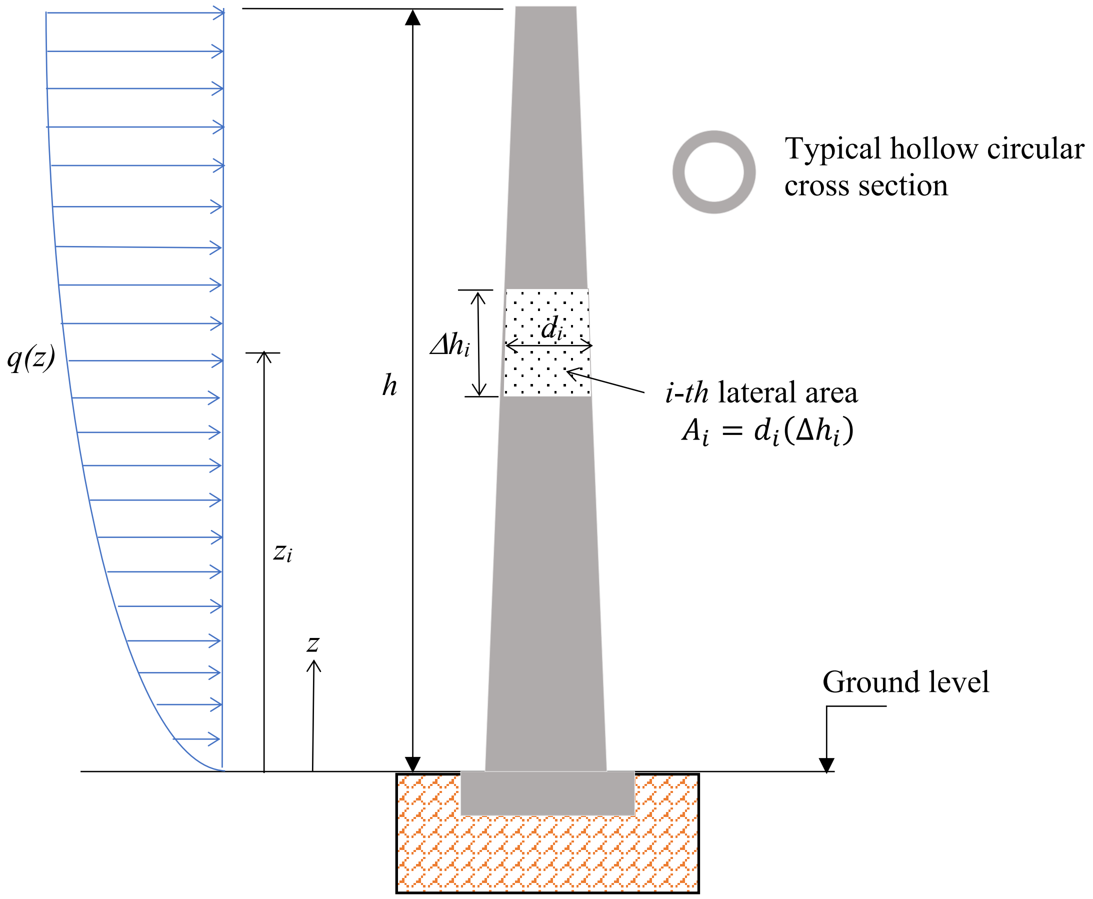

Figure 1 – Geometry of a concrete chimney based on DIN 1056(2005) wind load calculation standard.

The reference design wind speed in mph (m/s), which shall be denoted as V_r, shall be the 3-second gust wind speed at 33 ft (10 m) over open terrain, where

$$V_r = (I)^{0,5} V_0 \tag{1}$$

This speed V shall be as specified by ANSI/ASCE 7-05. The importance factor I for all chimneys shall be 1,15. Topographic effects referenced in Section 6.5.7.1 of ANSI/ASCE 7-05 are omitted by ACI 307-08.
At a height z ft (m) above ground, the mean hourly design speed $\bar{V}(z)$ in ft/s (m/s) shall be computed from Eq. (2) below:

$$\bar{V}(z) = (1{,}47)V_r \left(\frac{z}{33}\right)^{0,154} \times (0{,}65) \text{ (U.S.)} \tag{2a}$$

$$\bar{V}(z) = V_r \left(\frac{z}{10}\right)^{0,154} \times (0{,}65) \text{ (SI)} \tag{2b}$$

The along-wind load for circular shapes, $w(z)$ per unit length at any height z ft(m) according to DAVENPORT (1967), shall be the sum of the mean load $\bar{w}(z)$ and the fluctuating load $w'(z)$.
The mean load $\bar{w}(z)$ in lb/ft (kN/m) shall be computed from Eq. (3):

$$\bar{w}(z) = C_{dr}(z) \times d(z) \times \bar{p}(z) \tag{3}$$

Where the drag coefficient for along-wind load is:

$$C_{dr}(z) = 0{,}65 \text{ for } z < h - 1{,}5d(h) \tag{4a}$$

$$C_{dr}(z) = 1{,}0 \quad \text{for } z \geq h - 1{,}5d(h) \tag{4b}$$

and $1{,}5d(h)$ shall not exceed 50 ft (15,24 m).
$\bar{p}(z)$ is the pressure due to mean hourly design wind speed at height z, lb/ft^2 (N/m^2):

$$\bar{p}(z) = 0{,}00119 K_d [\bar{V}(z)]^2 \text{ (U.S.)} \tag{5a}$$

$$\bar{p}(z) = 0{,}613 K_d [\bar{V}(z)]^2 \text{ (SI)} \tag{5b}$$

where $K_d = 0{,}95$ for circular chimneys.
The fluctuating load $w'(z)$, lb/ft (N/m), shall be taken equal to

$$w'(z) = \frac{3{,}0z \times G_{w'} \times M_{\bar{w}}(b)}{h^3} \tag{6}$$

where $M_{\bar{w}}(b)$ is the base bending moment, lb-ft (N.m), due to mean along-wind load $w'(z)$, and the gust factor $G_{w'}$ for along-wind fluctuating load is

$$G_{w'} = 0{,}3 + \frac{11{,}0[T_1 \times \bar{V}(33)]^{0,47}}{(h+16)^{0,86}} \text{ (U.S.)} \tag{7a}$$

$$G_{w'} = 0{,}3 + \frac{11{,}0[T_1 \times (\bar{V}(10)/0{,}3048)]^{0,47}}{((h/0{,}3048)+16)^{0,86}} \text{ (SI)} \tag{7b}$$

The resulting along wind load $w(z)$ (N/m) is equal to

$$w(z) = \bar{w}(z) + w'(z) \tag{8}$$

For preliminary design and evaluation of the critical wind speed V_{cr}, as described in Section 4.2.3.1 of ACI 307-08 the natural period of an unlined chimney T_1, in seconds per cycle, shall be permitted to be approximated using Eq. (8). For final design, however, the period shall be computed by dynamic analysis

$$T_1 = 5\frac{h^2}{\bar{d}(b)}\sqrt{\frac{\rho_{ck}}{E_{ck}}}\left(\frac{t(h)}{t(b)}\right)^{0,3} \quad (9)$$

Where $\bar{d}(b)$ is the mean diameter at bottom of chimney, ρ_{ck} is the mass density of concrete, E_{ck} is the modulus of elasticity of concrete, $t(b)$ is the thickness of concrete shell at bottom and $t(h)$ is the thickness of concrete shell at top.
Across-wind load for circular shapes according to ACI 307-08 - A general solution for the across-wind response of circular chimneys with any geometry was developed by Vickery (1993).
According to section 4.2.3.1 of ACI 308-08, across-wind loads due to vórtex shedding in the first and second modes shall be considered in the design of all chimney shells when the critical wind speed V_{cr} is between 0,50 and 1,30 $\bar{V}(z_{cr})$, where $\bar{V}(z_{cr})$ is the mean hourly design wind speed at $z_{cr} = (5/6)h$. Across-wind loads need not be considered outside this range.

$$V_{cr} = \frac{fd(u)}{S_t} \quad (10)$$

$$S_t = 0,25F_{1A} \quad (11)$$

$$F_{1A} = 0,333 + 0,206\log_e\left(\frac{h}{d(u)}\right), \text{but } 0,60 < F_{1A} < 1,0 \quad (12)$$

where f is the frequency in Hz, $d(u)$ the mean outside diameter of upper third of chimney, S_t the strouhal number and F_{1A} the strouhal number parameter.
Across-wind response in the second mode shall be considered if the critical wind speed V_{cr2}, as computed by Eq. (1), is between 0,50 and 1,30$\bar{V}(z_{cr})$ where $\bar{V}(z_{cr})$ is the mean hourly wind speed at $z_{cr} = (5/6)h$.

$$V_{cr2} = \frac{5d(u)}{T_2} \quad (13)$$

Where $d(u)$ is the mean outside diameter of upper third of chimney and is the period T_2 in seconds per cycle for an unlined shell may be estimated by Eq. (10). For final design, T_2 shall be calculated by dynamic analysis

$$T_2 = 0,82\frac{h^2}{\bar{d}(b)}\sqrt{\frac{\rho_{ck}}{E_{ck}}}\left[\frac{t(h)}{t(b)}\right]^{0,09}\left[\frac{\bar{d}(h)}{\bar{d}(b)}\right]^{-0,22} \quad (14)$$

Where $\bar{d}(b)$ and $\bar{d}(h)$ are the mean diameter at bottom and top of chimney, respectively, ρ_{ck} is the mass density of concrete, E_{ck} is the modulus of elasticity of concrete, $t(b)$ is the thickness of concrete shell at bottom and $t(h)$ is the thickness of concrete shell at top.
Circumferential bending moment according to ACI 307-08 - The maximum circumferential bending moments due to the radial wind pressure is computed according the section 4.2.3.1 of ACI 308-08.
Wind deflection criteria according to ACI 307-08 - The maximum lateral deflection of the top of a chimney before the application of load factors shall not exceed the limits set forth by Eq. (12) of ACI 308-08.

$$Y_{max} = \frac{0,04h}{12} \quad (15)$$

Procedure for discrete dynamic analysis according to NBR 6123:1988

The ABNT NBR 6123:1988 [2] standard presents the discrete method for the calculation of the structures subjected to dynamic effects due to atmospheric turbulence, recommended for general cases of buildings and other structures, where there are variable properties with height.

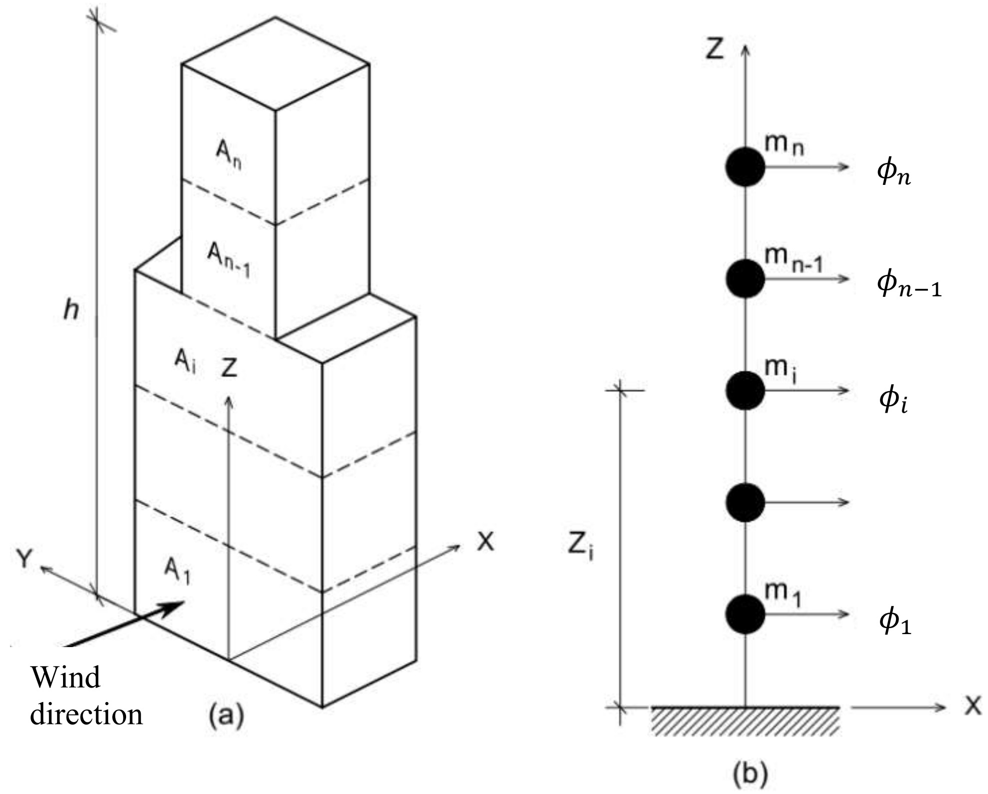

Figure 2 - Model for the discrete dynamic model according to ABNT NBR 6123:1988 standard.

In this work the discrete model is used for the analysis of a concrete chimney (example presented in annex I.2 of this standard).
The discrete model can be represented according to Figure 1, where ϕ_i is the displacement corresponding to the i-th coordinate; A_i is the area of influence corresponding to the i-th coordinate; m_i is the discrete mass corresponding to the i-th coordinate ; z_i is the height of i-th element from the ground level; n is the number of degrees of freedom (i = 1, 2, ..., n);
Once the discretization of the structure is established, the natural frequencies f_j and the modal form corresponding to the j-th mode, for j = 1, 2, ..., r, where r < n, and n is the number of modes retained in the solution.
For slender structures or structures with heavily variable rigidities, the contributions of modes 1, 2, etc., must be computed successively until the equivalente forces regarding the last calculated mode are negligible.
For each mode of vibration j, the total force due to the wind in the direction of the x-axis is given by

$$F_j = \sum_{i=1}^{n} F_i = \sum_{i=1}^{n} (\bar{F}_i + \hat{F}_i) \tag{16}$$

Where the average force $\bar{F}_i$ is given by

$$\bar{F}_i = \bar{q}_0 b^2 C_{dr} A_i \left(\frac{z_i}{z_r}\right)^{2p} \tag{17}$$

Where C_{dr} is the drag coefficient corresponding to the *i-th* coordinate; z_{ref} is the reference height, equal to 10 meters; b and p are coefficients related to the terrain type.
The mean pressure is given by

$$\bar{q}_0 = 0{,}613\left(\bar{V}_p\right)^2 \tag{18}$$

where $\bar{q}_0$ and the design velocity $\bar{V}_p$ are expressed in N/m2 and m/s, respectively. The floating force $\hat{F}_i$ is given by

$$\hat{F}_i = F_H \psi_i \phi_i \tag{19}$$

where

$$F_H = \bar{q}_0 b^2 A_0 \frac{\sum_{i=1}^{n} \beta_i \phi_i}{\sum_{i=1}^{n} \psi_i \phi_i^2} \xi \tag{20}$$

$$\beta_i = C_{dr} \frac{A_i}{A_0} \left(\frac{z_i}{z_r}\right)^{p} \tag{21}$$

In the above equations, m_o and A_o are arbitrary reference values of mass and area, respectively; ξ is the dynamic amplification coefficient, proposed for the five land categories; ζ is the critical damping ratio, proposed for several types of structures in ABNT NBR 6123:1988.

Design wind loads comparison between ACI 307-08 and NBR 6123-88 standards

Comparisons between above standards are presented in Table 1.
Table 1 – Design Wind loads comparison between ACI 307-08 and ABNT NBR 6123:1988.

Item	ACI-307-08	ABNT NBR 6123:1988
Drag coefficient (*Cdr*)	0,65(lower part) or 1,0(higher part)	0,6 (constant value)
Importance factor	1,15 (*I*)	1,0 (factor S_3)
Design wind speed	$V_r = (I)^{0,5} V_0$ $\bar{V}(z) = 0{,}65\left(\frac{z}{10}\right)^{\alpha} V_r$	$V_p = 0{,}69 V_0 S_1 S_3$ $\bar{V}(z) = 0{,}69\left(\frac{z}{10}\right)^{p} V_0 S_1 S_3$
Power law factor of wind speed	α = 0,154	p = 0,15
Pressure due to mean hourly design wind speed at height *z*	$\bar{p}(z) = 0{,}613 K_d [\bar{V}(z)]^2$ (SI)	$\bar{q}_0 = 0{,}613\left(\bar{V}_p\right)^2$
Mean load $\bar{w}(z)$ and $\bar{F}_i$	$\bar{w}(z) = C_{dr}(z) \times d(z) \times \bar{p}(z)$	$\bar{F}_i = \bar{q}_0 b^2 C_{dr} A_i \left(\frac{z_i}{z_r}\right)^{2p}$
Fluctuating load $w'(z)$ and $\hat{F}_i$	$w'(z) = \frac{3{,}0 z \times G_{w'} \times M_{\bar{w}}(b)}{h^3}$ $G_{w'} = 0{,}3 + \frac{11{,}0[T_1 \times (\bar{V}(10)/0{,}3048)]^{0{,}47}}{((h/0{,}3048)+16)^{0{,}86}}$ (SI)	$\hat{F}_i = F_H \psi_i \phi_i$ $\psi_i = m_i/m_0$ $F_H = \bar{q}_0 b^2 A_0 \frac{\sum_{i=1}^{n} \beta_i \phi_i}{\sum_{i=1}^{n} \psi_i \phi_i^2} \xi$ $\beta_i = C_{dr} \frac{A_i}{A_0}\left(\frac{z_i}{z_r}\right)^{p}$
Across-wind loads due to vórtex shedding in the first and second modes, when the critical wind speed V_{cr} is between 0,50 and 1,30 $\bar{V}(z_{cr})$, where $\bar{V}(z_{cr})$ is the mean hourly design wind speed at $z_{cr} = (5/6)h$.	$V_{cr1} = \frac{f d(u)}{S_t}$ $S_t = 0{,}25 F_{1A}$ $F_{1A} = 0{,}333 + 0{,}206 \log_e \left(\frac{h}{d(u)}\right)$ $V_{cr2} = \frac{5 d(u)}{T_2}$	Not implemented

For NBR 6123-88 only: Category II – Class C (p = 0,15 b =1,0) and V_0 is the 3-second gust speed at 10 m over open terrain.

Concrete chimney structure description

The structure of the chimney in this work is shown in the example of Annex I of the standard ABNT NBR 6123:1988 and also analysed by CARDOSO JR. (2011), ALGABA (2016) and CARVALHO *et al.* (2019). Tables 2 and 3 present the characteristics of the chimney and the properties of the adopted model.
The elasticity modulus considered for the concrete is 26,22 GPa and Poisson coefficient equal to 0,2. The terrain was considered Type III and the critical damping ratio equal to $\zeta = 0{,}01$ (reinforced concrete intrinsic damping). The factors S_1 and S_3 are taken equal to 1,0 and the basic velocity V_o is equal to 40,0 m/s. The total height of the chimney is 180 m, with Class C and the terrain rugosity is type III, where according to Table 21 of ABNT NBR 6123:1988 $F_r = 0{,}95$; $p = 0{,}115$ and $b = 0{,}93$.
More details of the discrete model procedure application according to ABNT NBR 6123:1988 in chimney structure can be seen in Annex I of this standard. The numerical model developed and the application of the proposed procedure will be presented as follows.

Table 2 - Characteristics of the chimney according to ABNT NBR 6123:1988 and CARDOSO JR. (2011).

Element	z (m)	External diameter (m)	Wall thickness (m)	Moment of inertia(m^4)
1	0 - 20	9,56	0,6	170,41
2	20 - 40	8,97	0,6	138,8
3	40 - 60	8,35	0,48	92,87
4	60 - 75	7,81	0,35	56,77
5	75 - 90	7,34	0,25	34,59
6	90 - 105	6,89	0,22	25,85
7	105 - 120	6,43	0,2	18,86
8	120 - 135	5,98	0,17	13,36
9	135 - 150	5,61	0,17	10,77
10	150 - 165	5,27	0,17	8,85
11	165 - 180	4,92	0,17	7,18

Table 3 – Properties of the structure according to ABNT NBR 6123:1988 and ALGABA(2016).

z(m)	ϕ_1	ϕ_2	ϕ_3	m_i (kg)	$A_i(m^2)$	C_{dr}
0	0,000	0,000	0,000	0	0	0,6
20	0,010	-0,046	0,102	1254000	282,5	0,6
40	0,037	-0,159	0,281	750000	173,2	0,6
60	0,085	-0,311	0,402	463800	141,4	0,6
75	0,137	-0,428	0,368	292500	114,0	0,6
90	0,207	-0,517	0,170	232500	107,2	0,6
105	0,298	-0,540	-0,164	195000	99,9	0,6
120	0,409	-0,461	-0,500	174400	93,0	0,6
135	0,540	-0,250	-0,636	163100	86,9	0,6
150	0,687	0,093	-0,400	153700	81,6	0,6
165	0,842	0,526	0,202	146200	76,4	0,6
180	1,000	1,000	1,000	70900	36,3	0,6

Note: Three first three natural frequencies of the chimney structure are according to ALGABA(2016) are:

$$f_1 = 0{,}262\ Hz;\ f_2 = 0{,}941\ Hz;\ f_3 = 2{,}156\ Hz \tag{22}$$

Numerical results of the discrete method of the chimney according to ABNT NBR 6123:1988 standard are presented in Table 4.

Table 4 - Results of the discrete method of the chimney according to ABNT NBR 6123:1988.

$z(m)$	$A_i(m^2)$	A_i/A_0	ϕ_i	m_i (kg)	β_i	$\beta_i\phi_i$	ψ_i	$\psi_i\phi_i^2$	$\bar{F}_i$ (kN)	$\hat{F}_i$ (kN)	F_i (kN)	M_i (kN · m)
0	0	0,000	0,000	0	0,0000	0,0000	0,0000	0,000	0,00	0,00	0,00	0,00
20	282,5	0,219	0,010	1254000	0,1491	0,0015	1,2540	0,000	75,65	4,80	80,45	1609,04
40	173,2	0,134	0,037	750000	0,1039	0,0038	0,7500	0,001	59,94	10,62	70,56	2822,52
60	141,4	0,109	0,085	463800	0,0914	0,0078	0,4638	0,003	56,86	15,09	71,95	4316,73
75	114	0,088	0,137	292500	0,0768	0,0105	0,2925	0,005	49,79	15,34	65,12	4884,13
90	107,2	0,083	0,207	232500	0,0747	0,0155	0,2325	0,010	50,08	18,42	68,50	6165,17
105	99,9	0,077	0,298	195000	0,0717	0,0214	0,1950	0,017	49,41	22,24	71,65	7523,37
120	93	0,072	0,409	174400	0,0684	0,0280	0,1744	0,029	48,33	27,30	75,63	9075,28
135	86,9	0,067	0,540	163100	0,0653	0,0353	0,1631	0,048	47,17	33,71	80,88	10918,41
150	81,6	0,063	0,687	153700	0,0625	0,0430	0,1537	0,073	46,05	40,41	86,47	12969,79
165	76,4	0,059	0,842	146200	0,0596	0,0502	0,1462	0,104	44,67	47,11	91,78	15143,50
180	36,3	0,028	1,000	70900	0,0288	0,0288	0,1709	0,171	21,92	65,40	87,32	15717,96

$$F_H = 382{,}71\ \text{kN};\ m_0 = 10^6\ \text{kg} \tag{23}$$

Results for the generalized total forces acting at the base of the Chimney: horizontal force F = 850,31 kN and bending moment: M = 91,15 MN.m.

Numerical results of the chimney according to ACI 307-08 standard are presented in Table 5.

Table 5 - Results of the chimney according to ACI 307-08 standard.

$z(m)$	$A_i(m^2)$	A_i/A_0	$\bar{V}(z)$ (m/s)	$\bar{p}(z)$ (kN/m²)	$\bar{w}(z)$ (kN/m)	$M_{\bar{w}}(b)$ (kN · m)	$w'(z)$ (kN/m)	$w(z)$ (kN/m)	F_i (kN)	M_i (kN · m)
0	0	0,000	0,000	0,000	0,00	0,00	0,0000	0,000	0,00	0,00
20	282,5	0,219	31,019	0,560	3,48	696,39	0,7020	4,184	123,64	2472,77
40	173,2	0,134	34,510	0,694	4,04	2426,25	1,4041	5,448	105,19	4207,65
60	141,4	0,109	36,731	0,786	4,26	4264,42	2,1061	6,371	107,88	6472,79
75	114	0,088	38,014	0,842	4,27	4325,51	2,6327	6,905	100,79	7559,02
90	107,2	0,083	39,096	0,890	4,25	5255,29	3,1592	7,406	108,16	9734,63
105	99,9	0,077	40,034	0,933	4,18	6113,21	3,6857	7,866	114,05	11974,96
120	93	0,072	40,865	0,972	4,06	6858,87	4,2123	8,277	119,71	14365,33
135	86,9	0,067	41,612	1,008	3,92	7496,17	4,7388	8,658	125,82	16985,93
150	81,6	0,063	42,292	1,042	3,80	8118,68	5,2654	9,064	131,83	19775,05
165	76,4	0,059	42,917	1,073	3,67	8680,30	5,7919	9,466	137,23	22643,18
180	36,3	0,028	43,495	1,102	5,42	14025,29	6,3184	11,739	86,61	15589,73

Results for the generalized total forces acting at the base of the Chimney: horizontal force F = 1260,91 kN and bending moment: M = 131,78 MN.m.

Numerical results for the across-wind response according to ACI 307-08 standard

According to section 4.2.3.1 of ACI 308-08, across-wind loads due to vórtex shedding in the first and second modes shall be considered in the design of all chimney shells when the critical wind speed V_{cr} is between 0,50 and 1,30 $\bar{V}(z_{cr})$, where $\bar{V}(z_{cr})$ is the mean hourly design wind speed at z_{cr} = (5/6)h.
Across-wind loads need not be considered outside this range.

$$z_{cr} = (5/6)h = (5/6) \times 180 = 150 \text{ m} \quad d(u) = 5{,}98 \text{ m} \tag{25}$$

$$V_r = (I)^{0{,}5} V_0 = (1{,}15)^{0{,}5} \times 40 \text{ m/s} = 42{,}89 \text{ m/s} \tag{26}$$

$$\bar{V}(z_{cr}) = V_r \left(\frac{z_{cr}}{10}\right)^{0{,}154} \times (0{,}65) = 42{,}89 \times \left(\frac{150}{10}\right)^{0{,}154} \times 0{,}65 = 42{,}30 \text{ m/s} \tag{24}$$

$$F_{1A} = 0{,}333 + 0{,}206 \log_e \left(\frac{h}{d(u)}\right) = 0{,}333 + 0{,}206 \log_e \left(\frac{180}{5{,}98}\right) = 1{,}03 > 1{,}0 \therefore F_{1A} = 0{,}999 \; (0{,}60 < F_{1A} < 1{,}0) \tag{28}$$

Numerical results for the across-wind response according to ACI 307-08 standard are presented in Table 6.

Table 6 - Results of the across-wind response according to ACI 307-08 standard.

Across-wind mode	Critical wind speed	Check across-wind effect	Condition
1st mode	$S_t = 0{,}25 F_{1A} = 0{,}25 \times 0{,}999 = 0{,}25$ $V_{cr1} = \frac{f d(u)}{S_t} = \frac{0{,}262 \times 5{,}98}{0{,}25} = 6{,}27 \text{ m/s}$	$V_{cr1} < 0{,}5 \, \bar{V}(z_{cr}) = 21{,}15 \text{ m/s}$	Not critical fro 1st mode
2nd mode	$V_{cr2} = \frac{5 d(u)}{T_2} = \frac{5 \times 5{,}98}{(1/0{,}941)} = 28{,}13 \text{ m/s}$	$V_{cr2} < 1{,}3 \, \bar{V}(z_{cr}) = 55{,}0 \text{ m/s}$	Critical fros second mode

Numerical results for the generalized total forces acting at the base of the Chimney, according to ACI 307-08 and ABNT NBR 6123:1988 standards, are presented in **Table 7.**

Table 7 – Results for the generalized total forces acting at the base of the Chimney according to ACI 307-08 and ABNT NBR 6123:1988 standards.

Item	ACI-307-08	ABNT NBR 6123:1988	Relative difference (%)
Total horizontal force F at the base	1260,91 kN	850,31 kN	48,29
Total bending moment at the base	131,78 MN.m	91,15 MN.m	44,57

Conclusions

From the results of table 7 the bending moment at the base of the chimney for the ACI-307-08 standard is 44,57% higher than the corresponding ones for ABNT NBR 6123-88 and it is possible to consider into the analysis across-wind effects, circumferential and thermal moments. Therefore, the wind load calculation for the chimney wind using ACI-307-08 is more complete and up-to-date than ABNT NBR 6123:1988, currently under technical review.
It has been shown the numerical results for the concrete chimney analyzed that across-wind forces shall be considered in combination with along wind effects as specified by ACI-307-08 standard.
Finally future studies comparisons using CICIND (2001) and EN 13084-2 (2007) standards are recommended.

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