RELIABILITY OF INDUSTRIAL CHIMNEYS AFFECTED BY VERTICAL REINFORCEMENT CORROSION

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Abstract. *Reliability of a reinforced concrete chimney is analysed considering probabilistic models for the effects of wind loads and the principles provided in Eurocodes. Corrosion of reinforcement due to carbonation is considered. Obtained reliability indices are compared with the target levels indicated in the EN and ISO standards. Sensitivity analysis identifies the parameters that have a significant impact on structural reliability, namely wind velocity and time-invariant wind pressure parameters. The values of these parameters can be updated based on measurements and a more economic design can be achieved.*

Keywords

Structural reliability, industrial chimney, wind load, carbonation.

1. Introduction

Industrial reinforced concrete chimneys are usually designed by the method of partial factors described in Eurocodes. An alternative and more advanced method for reliability verification of concrete structures is described in documents of *fib*. ISO 13822 for the assessment of existing structures [1] provides a general guidance on linking reliability analysis with in-situ measurements. EN 1990 [2] indicates annual target reliability index $\beta_t = 4.7$ for a medium class of failure consequences (CC2).

At present the Eurocodes provide no specific guidance on the target levels for existing structures. Appropriate values might be obtained from ISO 2394:2015 [3] where the target reliability index of $\beta_t = 3.3$ is provided for a medium consequence class and large relative cost of safety measures; the latter being deemed to be relevant for existing structures (note that these assumptions are adopted in the 2020 draft of *fib* Model Code 2020).

2. Reliability analysis

2.1. Description of the Construction

The presented analysis is focused on the industrial chimney designed by Eurocodes; see Kašparů [4]. The effect of vortex shedding according to EN 1991-1-4 is considered. The same chimney was also investigated in the previous study [5] that provided background information for this extended contribution where more detailed probabilistic assessment is presented.

The examined critical cross-section is located at the bottom of the chimney at the level of the flue gas inlet. The height of the chimney is 120 m. The outer diameter at the bottom of the chimney is 7.8 m with a wall thickness of 400 mm, at the top the outer diameter is 5.2 m with a thickness of 220 mm. At both surfaces steel reinforcement consists of Ø12 - 16 profiles with spacing of 200 - 250 mm.

2.2. Basic Variable

A reference period of one year is selected for reliability analysis and thus annual maxima of the wind load are considered. The limit state function reads:

$$\theta_R M_R = A\, c_a c_s c_r^2\, m_q v_b^2 \qquad (1)$$

where θ_R is the related model uncertainty, A is a deterministic parameter for determining the moment in the critical cross section from the specified wind pressure distribution, including the conversion from wind velocity to wind pressure, c_d the dynamic factor, c_s the construction size coefficient, c_r^2 the roughness factor, m_q the model coefficient considering model uncertainty, and v_b is the annual maximum of basic wind velocity. Flexural resistance, M_R, is obtained using Fine [6]; second order effects are neglected. An axial strength N_R is considered deterministic due to negligible variation when compared to the wind pressure effect. The ECOV method [7] is used to estimate coefficient of variation of resistance (CoV) at the critical cross-section, V_R.

Tab.1: Models of basic variables.

Basic variable	Dist.	Mean	Mean / X_k	CoV	References
Resistance model uncertainty, θ_R	LN	1.0	1.00	0.05	JCSS [8]
Moment resistance, M_R	LN	112 MNm	1.06	0.04	CoV based on the ECOV method [7].
Roughness factor., c_r^2	LN	1.0	1.00	0.05	[9]
Construction size coefficient, c_s	LN	1.0	1.00	0.15	[9]
Dynamic factor, c_d	LN	1.0	1.00	0.20	[9]
Model coefficient, m_q	LN	0.8	0.80	0.20	[9]
Wind velocity, v	GUM	15.9 m/s	0.64	0.19	Annual maximum based on measurements at the nearest meteorological station, hourly records available for 40 years [10].

GUM = Gumbel; LN = lognormal

The method is based on the assumption of a lognormal distribution of resistance and the estimates of resistance determined for the mean ($M_{R,m}$) and characteristic ($M_{R,k}$) values of material parameters:

$$V_R = \frac{1}{1.65} \ln \frac{M_{R,m}}{M_{R,k}} \quad (2)$$

All basic variables for reliability analysis are shown in Tab. 1.

The reliability analysis is performed using the FORM method. In the case of no degradation, annual reliability index $\beta = 4.1$ is below the Eurocode target of 4.7 for a medium consequence class. This finding is consistent with the observations from the previous studies where wind-dominated structures designed by the partial factor method have been found to have lower reliability levels in comparison to the Eurocode target levels.

2.3. Sensitivity Analysis

The FORM sensitivity analysis was also performed as a part of the reliability analysis. The sensitivity indices α in Fig. 1 express the influence of individual parameters on overall reliability. It appears that the parameters dominating reliability of the chimney are wind velocity v_b and the time-invariant wind pressure parameters c_d, c_s, c_r^2 and m_q. These parameters should be updated based on measurements, wind tunnel tests, or proven (properly validated) numerical methods to improve structural design.

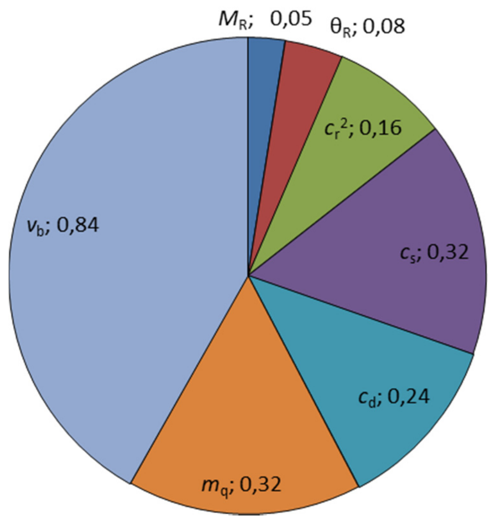


Fig. 1: Comparison of sensitivity parameters $|\alpha|$ for individual input parameters.

Many chimneys are in power plants that will be shut down in a few years. Therefore, it is no longer economically beneficial to repair these chimneys. However, their failures will likely cause considerable economic losses, and thus it is important to investigate the effect of carbonation-induced corrosion on their reliability and improve predictions of remaining service life of industrial chimneys.

This study does not consider the effect of repairs during the service life of the chimney. The influence of maintenance on corrosion rate and an approach to maintenance optimization was presented in [11].

It is assumed that structural resistance is directly proportional to the area of vertical (longitudinal) reinforcement A_s and that a uniform corrosion is always initiated when the carbonation front reaches the reinforcement.

3. Reliability Affected by Corrosion

Many of industrial chimneys are in operation for longer periods than their service life and visual inspections often reveal cracks due to corrosion or spalling of concrete.

Along with chloride ingress, carbonation of concrete cover is a major factor leading to reinforcement corrosion in reinforced concrete structures. The probability models for the rate of carbonation and carbonation-induced corrosion rate are provided by the JCSS [8].

The monitoring results provided by the leading Czech power producer suggest that the measured values of carbonation depth for the outer and inner surfaces differ negligibly and, for the sake of simplification, the same carbonation rate is considered for both surfaces in this study. The effect of this simplification will be analysed within future research. Under the simplified assumption that the relationship between the moment resistance and the area of reinforcement is linear (spalling of concrete cover is neglected), time-dependent moment resistance can be obtained as follows:

$$M_R(t) = M_R(t=0)\Delta deg(t) \quad (3)$$

where $\Delta deg(t)$ is the parameter expressing the relative loss of the reinforcement area due to carbonation-induced corrosion in time. The relative loss of reinforcement is determined as follows [8]:

$$\Delta deg(t) = \frac{A_s(t)}{A_{s,0}} = \frac{(d - 2v_{corr}t_{corr})^2}{d^2} \quad (4)$$

where:

- t - time since construction; [years]
- $A_{s,0}$ - area of reinforcement on the beginning of the service life ($t = 0$); [mm^2]
- $A_s(t)$ - area of reinforcement in time t; [mm^2]
- t_{corr} - corrosion time in years:

$$t_{corr} = \max(0; t - t_{ini}) = \max[0; t - (C/a)^2] \quad (5)$$

where t_{ini} is time to corrosion initiation ($D(t_{ini}) = C$).

The carbonation rate depends particularly on the quality of concrete and on external factors like humidity and the air concentration of carbon dioxide. The model is derived from measurements on cooling towers with a high coefficient of variation $V_D = 0.35$:

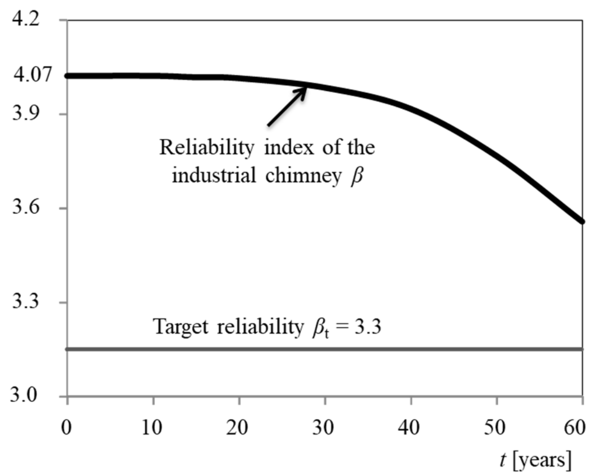
$$D(t) = a\sqrt{t} = 5.9\sqrt{t} \quad (6)$$

where a = 5.9 mm/√year is the parameter of carbonation rate according to [5]; see [12] for further discussion. The probabilistic models of the basic variables related to corrosion progress are given in Tab. 2.

Tab.2: Models of basic variables – carbonation-induced corrosion.

Basic variable	Dist.	Mean	CoV	Note
Concrete cover, C	LN	45 mm	0.2	CoV based on the measurements.
Corrosion rate, v_{corr}	W	5 µm	1.4	Based on [2] – the high CoV could be significantly reduced by measurements.
Diameter of reinforcement, d	DET	12 mm	-	-
Carbonation depth, $D(t)$	LN	5.9√t (in mm)	0.35	Based on [5].

DET = deterministic; LN = lognormal; W = Weibull.



Influence of the carbonation-induced corrosion on annual reliability index.

The Monte Carlo method is used to calculate time-dependent reliability of the chimney affected by carbonation-induced corrosion. Figure 2 shows that reliability of the chimney is moderately decreasing with time, reaching a value of 3.6 for t = 60 y. Obviously the Eurocode target is not achieved.

At present the Eurocodes provide no specific guidance on the target levels for existing structures. Appropriate values might be obtained from ISO 2394:2015 [3] where the target reliability index of β_t = 3.3 is provided for a medium consequence class and large relative cost of safety measures; the latter being deemed to be relevant for existing structures (as also recommended in the 2020 draft of *fib* Model Code 2020). This lower target level is not exceeded even when the effects of carbonation-induced corrosion are considered.

4. Further Research

This study provides a first insight into reliability of industrial chimneys exposed to wind pressure. Further research will address the following topics:

- verification of probabilistic models for wind pressure;
- validation of models for carbonation progress based on a larger number of experimental data for different ages of industrial chimneys and cooling towers;
- investigation of the effect of spatial variability of material and geometrical characteristics and environmental parameters on structural reliability;
- reliability updating based on observed crack widths and detailed investigations into the serviceability limit states.

The presented analysis deals only with the effect of corrosion on vertical reinforcement. Within further research more attention will be paid to horizontal reinforcement as it has a smaller concrete cover. Lack of horizontal reinforcement may lead to excessive cracking and need for repair. Ultimately the wide through cracks may subdivide the shaft into several segments, which could lead into the collapse [13].

5. Conclusions

The FORM sensitivity analysis identifies the parameters that have a significant impact on structural reliability - wind velocity and time-invariant wind pressure parameters. These parameters should be updated based on measurements, wind tunnel tests, or numerical models to improve structural design.

The reliability of the deteriorating chimney designed according to EN 1992-1-1 is critically compared with the recommendations of EN 1990 and ISO 2394. For a non-deteriorated chimney, the obtained annual reliability index of 4.1 is below the Eurocode target of 4.7. This finding is consistent with the observations from the previous studies where wind-dominated structures designed by the partial factor method have been found to have lower reliability levels in comparison to the Eurocode target levels.

Considering a lower target reliability level for existing structures according to ISO 2394, reliability of the degrading chimney seems to be sufficient. Preliminary results presented in this study thus indicate that carbonation may have a small effect on flexural resistance of the deteriorating chimney.

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References

[1] ISO 13822. *Bases for design of structures - Assessment of existing structures*, Geneve, Switzerland: ISO TC98/SC2, 2010.
[2] EN 1990. *Basis of structural design*, 2010.
[3] ISO 2394:2015 *General principles on reliability for structures*, Geneve, Switzerland, 2015.
[4] KASPARU, J. Static solution of concrete chimney, *MSc thesis*. Brno University of Technology, 2013.
[5] MLCOCH, J.; SYKORA, M. Reliability of Industrial Chimneys Affected by Carbonation-induced Corrosion. In: Proc. *12th International fib PhD Symp. in Civil Engineering. Prague*: CTU in Prague, 2018. p. 1019-1024. *fib* PhD Symposia. vol. 12. ISBN 978-80-01-06401-6.
[6] FIN EC – structural design software. ver. 2017.23 <https://www.finesoftware.eu>
[7] CERVENKA, V. 2013. Reliability-based non-linear analysis according to *fib* Model Code 2010. *Structural Concrete*, 14: 19–28. doi:10.1002/suco.201200022.
[8] JCSS. *JCSS Probabilistic Model Code*, chapter Environmental Exposure (12th draft, working document). Joint Committee on Structural Safety, 2019.
[9] SYKORA, M., M. HOLICKY, J. MARKOVA et al. Probabilistic Reliability Assessment of Existing Structures. Prague: Czech Technical University in Prague, CTU Publishing House, 2016. 108 pp. ISBN 978-80-01-05880-0.
[10] RYJÁČEK, P., J. ŽITNÝ, J. MARKOVÁ et al. Advanced methods of assessment of existing steel bridges exposed to wind actions, braking and acceleration forces, final report. Prague: Faculty of Civil Engineering CTU in Prague, 2017. 198 pp.
[11] MLCOCH, J., MARKOVA, J., SYKORA, M. Maintenance Optimization of Industrial Chimneys Exposed to Carbonation, *Transactions of the VSB - Technical University of Ostrava*. Construction Series. 2017, 17(2), 73-78. ISSN 1804-4824.
[12] SYKORA, M., et al. Predicting Service Life of Chimneys and Cooling Towers based on Monitoring. In: *Proc. fib Symposium 2017*. Maastricht, Cham: Springer International Publishing, 2017. pp. 1671-1679. ISBN 978-3-319-59470-5. DOI 10.1007/978-3-319-59471-2_192.
[13] NOAKOWSKI, et al.: Evaluation of Building Materials on the Basis of Measurement Regulations. An investigation into Industrial Chimneys. English issue of *VGB Kraftwerkstechnik*, Volume 72, No. 3, pp. 232-24

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