The effects of thermal overload in chimney caused by insulation damage

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Abstract. Modern approach to Structural Health Monitoring of building structures demands for reliable data concerning current technical condition of analysed structure or its parts. Data are provided preferably by means of non-destructive testing or visual inspections. When the analysed object is non- or hardly accessible (like in the case of tall industrial chimneys), remote techniques based on displacement, vibration or temperature control are appreciated. The current study focuses on the problem of thermal overload induced internal forces caused by insulation damage. Condensation inside the chimney affects the internal thermal insulation and migrates through the chimney wall from the inside. Moistening of the internal thermal insulation causes a progressive loss of its insulating properties. The corrosion of concrete and reinforcing steel is therefore progressive due to the increase in the temperature gradient in the reinforced concrete wall of the chimney, causing a large increase in internal forces, mainly tensile and shear stresses, and the appearance of additional cracks in the wall. The estimation of internal forces related to thermal influences given in the presented example indicates the significant threats that these influences may generate. In conclusion, it was pointed out that the proposed thermographic tests can be very helpful in monitoring temperature changes and signalling growing problems with the durability of chimney walls.

1. Introduction

Reinforced concrete structures exposed to environmental factors (wind, rain, sunlight) are exposed to corrosion. Corrosion initially concerns the reinforcement cover and, after its damage, also the steel reinforcement itself. This leads to a reduction in the strength and stiffness of the structure. The reduced stiffness results in increased displacement and a further, progressive reduction in strength.

The structures that are particularly exposed to the environment are industrial chimneys, where there is an additional negative influence of chemically aggressive flue gases. After leaving the chimney, these gases dissolve in the precipitation, becoming strongly acid rain. The flue gases also partially condense inside the chimney, causing corrosion of concrete and reinforcing steel on the inside of the chimney.

The degradation of the technical condition of all kinds of chimneys (including brick and concrete chimneys) may be caused by thermal [1,2] or mechanical [3,4]. The consequences of the destruction of their destruction have two main aspects:

- danger to the area at a considerable distance from the location of the object (due to the height of the chimney and the range after a possible fall),
- technological problems of an industrial installation, the functioning of which depends on the possibility of evacuating exhaust gases.
The use of non-destructive testing for the current assessment of the technical condition of chimneys enables the reaction and carrying out any necessary repairs or reinforcements at the stage when their conduct is not yet dangerous and does not require the suspension of production processes related to the chimney of technological lines [5].

2. Methods of evaluation of chimney deflection

Elastic deflection of the top of a chimney $y_w$ is caused by wind action. It can be calculated as follows:

$$y_w = \frac{\sum w_i H_0^2}{4EI_0}$$

where:

- $y_w$ – elastic deflection of the top of a chimney [m]
- $\sum w_i$ – sum of wind pressure of [kN]
- $H_0$ – height of a chimney-shaft [m]
- $E$ – Young modulus of a chimney-shaft (concrete) [MPa]
- $I_0$ – moment of inertia of the cross-section of a chimney-shaft on the level of connection with the foundation [m$^4$]
- $EI_0$ – stiffness of wall [MNm$^2$]

The above formula is approximate due to the variable moment of inertia of a chimney-shaft. If exact calculations are required, analytic equation of the deflection line should be used.

Elastic deflection of the top of a chimney $y_w$ should be calculated during the exploitation of a chimney. Calculated deflection should fulfil the following the conditions for reinforced concrete chimneys:

$$y_w < \frac{H_0}{200}$$

Defects in concrete and steel as well as cracks reduce the wall stiffness, in particular the value of the moment of inertia. Cracks appear when the bending moments in the chimney wall are greater than the cracking moment. Local reduction of stiffness will result in greater chimney deflection and greater susceptibility to dynamic impacts.

3. Methods of evaluation of stresses in chimneys: normal and shear stresses in concrete

State of stress in any point can be described by nine components (figure 1). Three of them, $\sigma_x$, $\sigma_y$, $\sigma_z$, are normal stresses, which act according to the axis of coordinate system and six of them, $\tau_{xy}$, $\tau_{xz}$, $\tau_{yx}$, $\tau_{yz}$, $\tau_{zx}$, $\tau_{zy}$, are shear stresses, which act perpendicularly to the corresponding axes of coordinate system. All of these components act on six walls of a cube perpendicular to each other.

The point in the centre of that cube can be described by the tensor of stress, which has got the following form (3) [6]:

$$\sigma_{ij} = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix}$$

In case of two-dimensional state of stress, the tensor of stress has got the following form (4):

$$\sigma_{ij} = \begin{bmatrix} \sigma_x & \tau_{xy} \\ \tau_{yx} & \sigma_y \end{bmatrix}$$
In both cases, two- and three-dimensional state of stress, we can rotate a cube or a flat element by a specific angle and then shear stresses disappear; normal stresses remain only on perpendicular directions to each other; we call them main stresses $\sigma_1$, $\sigma_2$, $\sigma_3$. In the flat state of stress, main stresses can be calculated with the use of the following formulas (5), (6):

$$\sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}$$

$$\sigma_2 = \frac{\sigma_x + \sigma_y}{2} - \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}$$

Main stresses are needed to determine places and directions of the propagation of cracks. Local wall heating causes additional tensile and compressive stresses, and in the case of imperfection an increase in bending moments. On the border of heated and colder fields shear stresses arise. Shearing and tensile is the cause of the appearance of cracks that can have any direction on the chimney wall.

4. Typical problems caused by destroyed internal thermal isolation

Internal thermal insulation, protecting the chimney wall against high temperature and large temperature fluctuations, is to limit the unfavorable increase in bending moment and tensile force in the chimney. It should be emphasized that any uneven temperature distribution on the chimney wall may cause local increases in horizontal and vertical internal forces and uncontrolled deflection of the chimney. This results in damage in the form of vertical and horizontal cracks, which additionally reduce the stiffness of the chimney.

As mentioned in the introduction, the internal thermal insulation of the chimney may deteriorate functionally or deteriorate (fall off) due to the ingress of an excessive amount of condensate into the surface of the chimney wall. Such a technological influence destroys concrete cover and reinforcement (figures 2, 3).

The thermographic photographs presented below were taken by authors in 2012 on a relatively new chimney (figure 4). It is shown where bright fields are places with high temperature, i.e. spaces with no insulation or with damaged insulation.

It should be emphasized that the revealed leaks in the internal insulation of reinforced concrete walls may cause a constant flow and increasing condensation of flue gas due to the reduction of its thermal insulation.
Figure 2. Chimney with damaged thermal protection

Figure 3. The destruction of concrete cover and reinforcement

Figure 4. The chimney on the left thermograms (external temperature 15 °C) revealing insulation imperfections: no thermal insulation more than two meters above and under platform; varied temperature distribution in chimney shaft. The right chimney measured in autumn time.

5. Basis of thermographic survey of chimney thermal insulation

As it was previously mentioned, the assessment of chimney technical condition by means of its insulation condition is considered as vital factor for the actual technical condition and durability assessment. Cautious control provides data for systematic elimination of major causes of chimney destruction throughout its life-time service [7,8].

Detailed description of thermographic methodology with regard to:

- thermal stresses,
- thermal and static load analysis,
- adopted assumptions,
- distribution of temperature in chimney wall in case of insulation discontinuity,

were given in authors’ recent publication (reference [9]).
6. Case study – evaluation of surface temperature load and resulting thermal load (DAWNE 9)

Summer time insolation and winter time frost may cause thermal conditions that differ significantly from original thermal conditions in course of chimney erection. Both extremal cases must be considered for the thermal analysis with regard to freedom of deformation that is limited. For the presented case study purposes, some assumptions and types of thermal effects were considered:

- \( v_0 = 10 \text{ m/s} \) – velocity of flue gas flow in the chimney
- \( t_{w,2} = 180^\circ \text{C} \) - operating temperature of flue gas at the chimney outlet
- \( t_{w,1} = 220^\circ \text{C} \) - operating temperature of flue gas at the chimney inlet
- \( T_{\text{min}} = -36^\circ \text{C} \) – external design temperature in winter (based on the national annex)
- \( T_{\text{max}} = +40^\circ \text{C} \) – external design temperature in winter (based on the national annex)
- The emergency flue gas temperature is assumed as 20% higher than the typical one
  - \( t_{wA,2} = 20^\circ \text{C} \) - emergency temperature of the flue gas at the chimney outlet
  - \( t_{wA,1} = 270^\circ \text{C} \) - emergency temperature of the flue gas at the chimney inlet

The emergency values were taken into the calculations. Thermal conductivity:

- \( \lambda_c = 1,74 \text{ W/mK (concrete)} \)
- \( \lambda_i = 0,05 \text{ W/mK (insulation – mineral wool)} \)
- \( \lambda_b = 1,30 \text{ W/mK (fire brick)} \)
- \( t_i \) – thickness of layers, \( t \) - thickness of concrete wall =0,24 m;
- \( r_i \) – outside radius of layer;
- \( r_z \) – outside radius of the shaft;
- \( t_1=0,24 \text{ m; (r}_1=2,82 \text{ m); t}_2=0,13 \text{ m; (r}_1=2,58 \text{ m); t}_3=0,11 \text{ m (r}_2=2,28 \text{ m);} \)
- \( E_c \) – Young’s elasticity modulus of a chimney-shaft, here \( E_c=33[\text{GPa}] \), concrete C30/37;
- \( \nu \) - Poisson coefficient, here \( =0,6 [-] \);
- \( \alpha \) - coefficient of linear expansion, here \( \alpha=0,00001 \ [1/\degree \text{C}] \);
- \( f_{ctm} = 2,9 \text{ MPa} \) – the mean tensile strength
- \( A_c \) – the cross-sectional area \( A = 1 \cdot 0,24 = 0,24 \text{ m}^2 \);
- \( I_0 \) – inertia moment of concrete wall, \( b t^3/12 = 0,00115 \text{ m}^4 \)
- \( W_1 = b \cdot t^3/6=0,096 \text{ m}^3 \)-section modulus, \( b = 1 \text{ m;} \)

The first load is an effect of difference between temperatures on the surface of the chimney concrete shell. There are two design situations: the first one is idealized, without degradation of insulation (immediately after chimney erection), and the second one is when part of insulation has degraded. This load is presented as the gradient of the temperature in the shaft. The second load is caused by the difference between the operating temperature during chimney service life and the initial temperature in particular segments. It is presented as surface temperature load (table 1).

6.1. First design situation – without insulation degradation

Thermal transmittance coefficient:

\[
\frac{1}{k} = \frac{1}{\alpha_n} + \sum \left( \frac{t_i}{\lambda_i} \cdot \frac{r_i}{r_z} \cdot \alpha_i \cdot \sum \right) + \frac{1}{\alpha_o}
\]

(7)

where:

- \( \alpha_n \) – inflow coefficient (the zone of the inner surface of the lining)
\[ \alpha_n = 8 + \nu_0 = 8 + 10 = 18 \frac{W}{m^2K} \]  

(8)

where:

\( \nu_0 \)– mean velocity of the flue gas, here \( \nu_0 = 10 \) m/s

\( \alpha_o = 24 \frac{W}{m^2K} \) – outflow coefficient (the outer surface of the shaft)

\( \kappa_i \) – correction coefficients considering wall curvature

\[ \kappa_i = \left( \frac{r_i}{r_i^0} \right)^{0.57} \]  

(9)

The temperature drops in a given layer and temperature drops for the inflow and outflow:

\[ \Delta T_i = k * \frac{t_i}{\lambda_i} * \kappa_i * \frac{r_{iz}}{r_i} * \Delta t \]  

(10)

\[ \Delta T_n = k * \frac{1}{\alpha_n} * \Delta t \]  

(11)

\[ \Delta T_o = k * \frac{1}{\alpha_o} * \Delta t \]  

(12)

\[ \Delta t = t_w - t_z \]  

(13)

The temperature at the boundary of each layer:

\[ T_j = t_w - \frac{k}{\alpha_n} * \Delta T - \sum_i \Delta T \]  

(14)

Temperature drops are different for different segments; this is due to external temperature drop with increasing height and variable thickness of the chimney wall. The differences in temperature is bigger during the winter, because of lower external temperature (figure 5).

Figure 5 shows temperature on surface of chimney in external temperature of 15°C. The values are different than calculated properly in ideal situation just after erection. Due to acting of flue gases situation, when chimney loses part of insulation, was considered.
Real values correspond to values we can obtain with 10 times worse insulation parameter of mineral wool panels (for damaged insulation approximately $\lambda_i = 0.5$ W/mK). External temperature of concrete shell is read from thermograph and rest values are calculated according to building physics.

### Table 1. Mean change and gradient of temperature on surface of every layer for external temperature $T_{\text{ext}} = 15^\circ$C

| Segm. no. | H [m] | Summer time $T_\text{int}$, $T_\text{hi}$, $T_\text{he}$ | Winter time $T_{\text{int}}$, $T_{\text{hi}}$, $T_{\text{he}}$, $T_{\text{i,e}}$, $T_{\text{c,e}}$, $T_{\text{ext}}$, $\Delta T_c$ |
|-----------|-------|-------------------------------------------------|------------------------------------------------------------------------------------------------|
| 1         | 2.5   | 40, -36                                         | 58, 2.5, 268, 262, 199, 101, 34, 68 |
| 2         | 15    | 38, -35                                         | 55, 15, 265, 256, 194, 96, 34, 63 |
| 3         | 30    | 39, -34                                         | 55, 30, 259, 249, 184, 95, 35, 60 |
| 4         | 45    | 38, -36                                         | 55, 45, 251, 237, 199, 97, 33, 65 |
| 5         | 60    | 38, -36                                         | 49, 60, 246, 228, 191, 87, 31, 59 |
| 6         | 75    | 37, -36                                         | 46, 75, 239, 221, 184, 82, 30, 53 |
| 7         | 90    | 36, -36                                         | 39, 90, 234, 212, 175, 74, 27, 48 |
| 8         | 105   | 36, -38                                         | 37, 105, 226, 205, 168, 68, 27, 42 |
| 9         | 120   | 35, -39                                         | 34, 120, 221, 198, 161, 61, 26, 36 |

#### 6.2. Increase in bending moments due to increase in temperature gradient

To obtain winter gradient of temperature distributions for reinforced concrete walls with damaged insulation we can proceed as below. To outside temperature during experiment ($15^\circ$C, col. 12 Tab. 1) we subtract outside temperature during winter ($-36^\circ$C figure 5) and this result add to col.13 Tab 1. We receive $\Delta T_c = 86 \div 118^\circ$deg. For further calculations it was assumed $\Delta T_c = 85$ deg.

The presented computing models do not average their results. They assume quite a sharp transition from one temperature field to another without a transition area.

In cylindrical cross-section of a chimney, as result of the difference between internal and external temperature, the three-dimensional state of stress appears [6] (figure 6). If we assume circularly-symmetrical temperature variation in the plane of the cross-section of the chimney, the invariability of temperature in the direction of the cylinder axis, constant concrete coat thickness and the fact that pitch-surface generators are parallel to each other, circularly symmetrical state of stress appears. It is characterized by three components: radial stresses $\sigma_r$, circumferential stresses $\sigma_\theta$ and longitudinal stresses $\sigma_z$. Radial stresses are small, and they can be ignored.

Circumferential stresses create the bending moment $M_\theta$ which acts on the chimney-shaft in the plane of cross-section. Longitudinal stresses create the bending moment $M_z$, which acts on the chimney-shaft in longitudinal planes determined by the axis and radius of the cylinder. $M_\theta$ demonstrates bending moment acting on the coat’s cross-section of the unit width measured along the pitch-surface generator (1 m). $M_z$ demonstrates the bending moment acting on the band of coat with its width limited by the unit’s central angle in radians.
Figure 6. Bending moments due to thermal stresses

\[ M_\theta = \frac{E*\alpha}{2*(1-\nu)} * (T_R - T_r) * L_1 \text{ [kNm/m]} \]  
\[ M_z = \frac{E*\alpha}{2*(1-\nu)} * (T_R - T_r) * L_2 \text{ [kNm]} \]  
\[ L_1 = \frac{r^2*R^2}{R^2-r^2} * (\ln R - \ln r) - \frac{R^2-r^2}{4*(\ln R - \ln r)} \]  
\[ L_2 = \frac{2*(R^3-r^3)}{3*(R^2-r^2)} * R^2 - \frac{2}{3} * R^2 - \frac{R^3-r^3}{9*(\ln R - \ln r)} \]

where:

- \( r, R \) - internal and external radius of the concrete cylindrical coat [m]
- \( T_R, T_r \) - temperature gradient on external and internal surface of a chimney-shaft, here=85 deg

\[ L_1 = 0.010 \]
\[ L_2 = 0.026 \]
\[ M_\theta = 102.9 \text{ kNm/m} \]
\[ M_z = 277.7 \text{ kNm/m} \]

The meridional and latitudinal bending moments caused by thermic are greater than the cracks moments and larger than those designed for this type of chimneys.

An example of bending moment that exceeds value of cracking moment (bending capacity) and calculated change in length of cylindrical shell were presented in Appendix A to reference [9].

Bending moments were presented in a form like on figure 7, due to gradient \( \Delta T \), and shear forces are additional quantities, whereby the forces assumed in the design are exceeded. Calculations were carried out for simplified static load diagrams.

The values of the bending moments and shear stresses indicate high additional stresses in concrete. As the horizontal band in the concrete wall with damaged insulation heats up, the band is “pushed” outside more strongly, whereby the bending moment arises.

7. Discussion
Damage to thermal insulation leads to an increase in the value of internal forces in the reinforced concrete wall of the chimney. Local reduction of insulation further increases shear stress. Increased bending moments and shear stress are the reason for additional cracks in the wall. Particularly cracks appear in technological joints between successive breaks in pouring concrete. These cracks reduce the stiffness and durability of the wall. Damage to the insulation consists in its settling and soaking.
The cause of insulation damage is rainwater penetrating through cracks from the outside of the reinforced concrete wall and smoke condensate penetrating from the inside through the ceramic wall thermal insulation. The reduced thermal insulation reduces the smoke temperature and causes its condensation. The cause of cracking is also the shrinkage of concrete often ignored in strength calculations. Repairing thermal insulation is very difficult for chimneys that have been in continuous use for decades. It seems that periodic drying of insulation should be provided for by airing, e.g. through openings in the reinforced concrete wall and special channels inside the insulation. Cracks in chimney repair by means of injection prevents degradation of the chimney wall and increases stiffness, but can’t dry damp thermal insulation.

8. Summary and conclusions
The example calculations presented in this paper indicate the possibility of a qualitative and quantitative assessment of the magnitude of internal forces and the accompanying stresses caused by thermal effects on the chimney mantle. Randomly localized internal temperature loads can cause cracking and reduce chimney stiffness and durability. Thanks to thermographic tests, these hazards can be monitored at any time, without forced breaks in the operation of the chimney and, consequently, stopping the technological processes. The sample calculations presented in the article, made on the basis of actual thermographic measurements, indicate the possibility of a reliable assessment of the value of internal forces and the accompanying stresses caused by thermal impact in the identified locations.

Thanks to thermographic tests, which are non-destructive and non-invasive tests, it is possible to monitor the threats leading to the degradation of the structure. During the calculations with the methods presented, it is necessary to consider the influence of local temperature gradients precisely and to apply mitigation at the border of adjacent stress fields.

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