Phenomenon of cracks in chimney walls

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Abstract. Cracked walls of chimneys have a serious impact on their durability. There are many reasons for chimney cracks. Among them, the most important is the impact of the environment in which the chimneys operate, the method of concrete care, the amount of reinforcement in the walls of the chimneys, the quality of concrete and the first start-up of the chimney. Cracks reduce the chimney's stiffness and cause increased corrosion of reinforcing steel and concrete. Repairs of scratched chimneys are most often reduced to injection of cracks and replacement of concrete cover.

1. Introduction

Direction of cracks in concrete shells in the phase of forming is approximately the same as the direction of the minor main stress. Cracks appear when the major main stress exceeds tensile strength of concrete f_{cds}.

Figure 1. Main stresses and direction of cracks

There are many reasons why cracks appear in concrete chimney-shaft [1-3]. In different phases of the lifetime of the object (design, construction, exploitation) different problems can arise. At the beginning of increased survivability, while concrete is maturing and later, when concrete starts to transfer first loads, both stresses from shrinkage and gradient of temperature can exceed tensile strength. During the exploitation phase, over time, other reasons for cracking come into being, i.e. corrosion of steel and fatigue [4-6]. When the chimney shell has been exploited for a long time, we can observe surface detachment and local inhomogeneity in concrete structure. Sometimes, existing chimney is exposed to previously unexpected impacts like vibrations [7] of various nature. The geometry can be than examined by means of various surveying techniques [8]. Actual quality of
chimney material may be examined using numerous non-destructive testing methods to achieve prospects for its increased survivability [9].

The most obvious reason for cracks in concrete chimney-shaft is wind action. However, during the design phase, tensile stresses are reduced so that they do not exceed tensile strength. Accordingly, wind is not usually a direct reason for cracking. More popular factors leading to cracking are thermal load (exhaust gases), amplitude of temperature (daily, yearly), shrinkage of concrete, uneven settlement of foundations, technology of construction (construction joints, formwork, vibration, curing) and aggressive environment. Furthermore, in chimneys where reinforcement bars are placed in two rows instead in one, more cracks appear.

2. Model of cracks

There are various models of cracks in theory of reinforced concrete. Most of them were based on the assumption that in the process of crack formation the cooperation between concrete and reinforcement is violated. The modulus of elasticity of reinforcement steel bars ($E_s = 205$ GPa) is several times greater than the modulus of elasticity for concrete ($E_c = 36-40$ GPa). Currently, reinforcement made of other materials (basalt, glass, etc.) is used and the modeling of concrete and composite material cooperation has also changed.

However, the assumptions from the theory of elasticity describing tangential stresses occurring on the surface of cooperation of concrete and reinforcement [7] remain unchanged:

$$\tau = (A_s / U) (d\sigma_s / dx)$$

and the constitutive equation given by Guyon

$$\tau = k \cdot u$$

in which:

- $A_s$ – cross-section of reinforcement
- $U$ – reinforcement bar perimeter
- $d\sigma_s / dx$ – increase of normal stress in reinforcement on section $dx$
- $u$ – elongation of reinforcement
- $k$ – proportionality factor

Before the crack, the reinforcement elongation $u$ is equal to the elongation of the concrete on the contact surface. Hooke's law shows

$$\sigma_s = E_s \varepsilon_s = E_s (du / dx)$$

From the equations (1), (2) and (3) it is obtained

$$(A_s / U) E_s (d^2u / dx^2) – ku = 0$$

The second-degree equation of equilibrium has a solution in the form

$$U = \alpha \cdot \exp(-\lambda x) + \beta \cdot \exp(-\lambda x)$$

$\alpha$, $\beta$ – constants of integration

$$\lambda^2 = ku / A_s E_s$$

$\lambda$ – is determined from the condition of equilibrium at the end of reinforcement

Crack elongation is the sum of the elastic and residual elongation

$$\Delta L^{tot} = \Delta L^E + \Delta L^{res}$$
For design purposes, it can be assumed that the value of residual elongation \( \Delta L_{\text{res}} \) is approximately equal to \( 1/3 \) value of the total elongation \( \Delta L_{\text{tot}} \). The theory of [6] assumes the validity of Bernoulli hypotheses of flat cross-sections.

Consequently, total strains \( \varepsilon^T \) have a linear distribution over their entire height.

\[
\varepsilon^T = \varepsilon_{\text{res}} + \varepsilon^E = A + B \cdot z \tag{8}
\]

The above analysis defines the "self-stresses" that occur after unloading the structure. Self-stresses are a source of initial tensile stresses that add up to stresses from external loads (e.g. wind, thermal loads). This model of cracks also allows to explain why the scratches remain after relieving the structure. This is graphically illustrated on figure 1. In addition, a similar distribution of self-stress arises during uneven wall drying and multiplies the value of tensile stresses (figure 4, [1,5]).

![Figure 2. Residual stresses in the beam before scratching [3]](image)

### 3. Impact of cracks on chimney walls on their durability [3]

There are many problems connected with reinforced concrete chimneys operating in the aggressive environment. Chimney exhaust fumes have a considerable influence on durability and longevity of chimney walls. Especially grave difficulties appear when it is impossible to disconnect the chimney from constant work. In such cases repair works are often ineffective and very expensive.

In designing chimney walls, no allowance is made for the appearance of larger cracks. Horizontal and vertical cracks can cause corrosion of concrete and steel bars. Cracks decrease the stiffness of chimney shell construction made from reinforced concrete. Local and global imperfections of chimney walls are increasing as the number of cracks becomes larger. Taking into account the above facts, cracks reduce the service life of chimneys. Horizontal and vertical cracks allow condensate water to infiltrate into the wall. It causes corrosion and damp of concrete walls and during winter time cracks become bigger due to glaciation water in cracks.

Problems with a large number of cracks in chimneys walls occurred in recent years in Poland. It was connected with changing regulations for the construction of chimneys, in particular the requirement for double reinforcement of concrete walls. Until the end of 20th century, reinforcement bars were located in one row, near the external surface. Due to the introduction of European Standards in Poland two rows of reinforcement are required. The regulation gives rise to construction difficulties because little space is left for reinforcement bars in a rather thin wall. Another problem if the increasing number of cracks in chimney insulation; also, their width increases. Improper placement of insulation results in increased bending moments and the cracks become wider. The following problem is condensate which leaks through joints and cracks. Increased temperature in the chimney wall and insulation, chemical activity of condensate, dampness in thermal insulation as well as badly made joints cause increased corrosion of steel and concrete. The result of these are many defects of concrete cover.

The appearance of cracks or loss of cover indicate the process of chimney degradation. Horizontal and vertical cracks can cause corrosion of concrete and steel bars. Cracks decrease stiffness of the shell construction of chimney made of reinforced concrete. Local and global imperfections of chimney...
walls are getting worse as the greater number of cracks increases. Taking into account these facts, cracks reduce the service life of chimneys. Horizontal and vertical cracks allow condensate water infiltrates into the wall. It causes corrosion and dank of concrete wall and during winter time cracks become bigger because of glaciation water infiltrating into cracks.

Figure 3. Cracks appearing in time, source: [5]

The problems with a large number of cracks on chimney walls occurred last years in Poland. It was connected with changing chimney regulations, and in particular with the regulations requiring double reinforcement of concrete walls. Until the end of 20th century reinforcement bars were located in one row, near the external surface. After European Standards were introduced in Poland two rows of reinforcement are required. It caused several difficulties in building chimneys because of the meagre space left for reinforcement bars.

Another problem is the increasing widths of cracks as well as their number in chimney insulation. Improper placement of insulation results in increased bending moments, and on cracks become wider. In designing chimney walls allowance is made for cracks no bigger than 0.1 mm. Horizontal and vertical cracks can caused corrosion of concrete and steel bars. Cracks decreases stiffness of reinforced concrete chimney shell construction. Local and global imperfections of chimney walls are increasing according to greater number of cracks. Taking into account these facts, cracks reduce the service life of chimneys. Horizontal and vertical cracks allow condensate water infiltrates into wall. It causes corrosion and dank of concrete wall and during winter time cracks become bigger because of glaciations water in cracks.

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4. Causes of cracks formation in concrete walls of chimney [5,6]

4.1. Cracks caused by low quality of materials

One of the basic reason for the appearance of cracks in chimney concrete-shafts is low quality of materials used for their construction (concrete and steel rebars). That phenomenon we can observe usually in old chimneys, which have been exploited for many years. There is another problem with chimneys -- their maintenance. Access to such construction is seriously limited, which stops early detection of cracks or any other damages.

4.2. Cracks caused by temperature

Thermal stresses can by caused by internal factors: heat of cement hydration, or by external factors: changes in temperature. In the first case, cracking is caused by temperature because insufficient insulation has been used. In the case of high temperature gradient, horizontal and vertical cracks can appear. Mistakes made during construction can also contribute to cracking, for instance the position of reinforcing bars too close to the geometric centre of the concrete-shaft wall. Gradient of temperature causes a bending moment, which again causes tensile stresses on the edges of the shaft. That stresses exceed tensile strength of concrete and steel rebars, which are too close to the internal surface of the concrete coating, and cannot transfer that bending moment. Insufficient concrete cover can also be a reason for cracking. If the cover is too thin, it can be damaged in areas where steel rebars are placed too close to the surface of the concrete coat.

Figures 4. Multiple cracks in concrete shell, source: [6]

Temperature can be another reason for the degradation of the insulation layer which prevents negative influence of exhaust gases and higher temperature on concrete shell. Destruction of the insulation layer and mortar layer as well exposing concrete to exhaust gases changing the alkaline character of concrete, which finally can be a reason of steel rebars corrosion. The effect of exhaust gases can be increased by high temperature and increased humidity. Influence of temperature can be magnified by construction mistakes, i.e. improperly made gas installation, which can lead to the lowering of gas temperature and to the liquefaction of gases. Liquefied gases fall down into the concrete shaft and can destroy the mortar layer. In that case the concrete shell is exposed to temperature higher than the designed temperature, which leads to the appearance of additional stresses, and finally to cracking.
4.3. Cracks are subjected to rheology phenomenon

One of the known reasons for the appearance of cracks is the changing of material properties, that is rheology [1]. The knowledge of the described redistributions of stress and deformation in the permissible working range of the structure is quite significant also when protective coatings are applied. In most cases, it is fully justified that the material used as a coating or insulation has no less deformation range than the underlying structure. Otherwise, damage to the coating may occur. The same applies to permissible stress states in the coating. A particular phenomenon is the appearing cracks on the structure, especially reinforced concrete one. They can be formed at the initial stage of concrete curing (with the most common shrinkage cracks), as well as during the use of the structure (figure 4) [4, 5].

![Figure 5. Stresses in cross section from shrinkage and creeping [1,4,7]: a) distribution of self-compressing, b) distribution of stresses in bending cross section, c) distribution of total stresses.](image)

Cracks in concrete are caused by exceeding the tensile strength in concrete cross section. In the case of concrete, where the bonding process is advanced, cracks are generally formed as a result of stresses caused by external loads. In concrete where the bonding process is in its initial phase, but the concrete is already hardened, cracks appear through self-compressing processes. The external effect is the so-called shrinkage cracks.

It can be assumed that shrinkage cracks are irreversible. In the course of exploitation, under stress loads, internal tensions occur, tensile and compression tensions. These stresses may be cyclical, e.g. when filling and emptying the tank. Tensile stresses cause further expansion of the existing cracks. Cracks arising from cyclic loads are mostly reversible. In some cases, for example in tanks, this effectively hinders the repair work, which is usually carried out without hydrostatic load.

4.4. Cracks caused by shrinkage

Shrinkage is a phenomenon of decreasing volume of material which is not the result of any load put to the object. Shrinkage can be classified into different types. Chemical shrinkage is the result of the decreasing volume of concrete products as a result of the hydrating reaction in comparison to the components of that reaction such as water, cement, additives. We can decrease the result of chemical shrinkage by proper curing of concrete. Plastic shrinkage takes place when concrete works in the plastic phase. It is a result of water evaporation from the surface of concrete. When the amount of that evaporated water is bigger than the amount of water that we deliver, cracks can appear. Cracks of that type are parallel to each other, and they can have considerable depth. Autogenous shrinkage takes place when still un-hydrated cement grains pull away water from capillary pores (the process of self-drying of concrete). The effect of autogenous shrinkage can be decreased by using cement with proper additives. The last type of shrinkage is caused by the drying of water from the surface of concrete. We cannot totally eliminate the negative effect of autogenous shrinkage; we can only decrease it. Displacements resulting from that type of shrinkage are the biggest.

The problem of shrinkage, we can observe in places of construction joints. During construction in such places, tensile stresses from shrinkage as well as tensile strength are growing. When we dismantle the formwork from the lower part, concrete starts drying fast; drying is limited in the higher part because of the presence of the formwork. While the lower part is already dry and thermally stable
(especially when the difference in temperature between placing concrete in the lower and the higher part was considerable), in the upper part, we can observe first thermal expansion (because of the heat from cement hydration) and the process of concrete maturity, which means hardening and chilling of concrete mix.

That leads to shrinkage, against which the lower part of concrete coat works (at this moment under compression). The upper part is under tension. Increasing tensile stresses in places of construction joints can lead to cracking in the upper part of wall.

![Figure 6. Crack in place of construction joint, source: [5].](image)

To avoid that situation, additional reinforcement is needed: vertical rebars for shearing stresses and horizontal for tensile stresses. Also, it is important to cure concrete in proper way to avoid too fast drying. Shrinkage can also lead to the growth of self-stresses. Especially when the thickness of a wall concrete shell is bigger than 60 cm, that type of stresses can have a big influence upon summary tensile stresses, and can lead to cracking. Against that phenomenon, we can use additional surface reinforcement.

4.5. **Cracks caused by creep**

Creep is the phenomenon of increasing displacement of material without increasing any load. In concrete chimneys, where high temperature appears, the effect of creep can be increased. The creep is especially sensitive to moisture level on concrete elements below 100°C; when that level is high the effect of creep occurs faster. Above 100°C, chemical and physical changes can also increase the effect of creep, which can weaken concrete and finally cause cracking. When the temperature is higher than 400 °C creep rate is growing very rapidly.

4.6. **Cracks caused by technology of construction**

Cracks can also appear as a result of improper construction. They can occur in places where the formwork is dismantled after the hardening process of concrete is finished.

Today, reinforcement in concrete chimney-shafts is placed on both sides of the wall, which can cause problems, especially when the spacing of rebars is small. Vibrators are very often placed in such a way that they touch both the rebars and the formwork. That can violate the bars in concrete during the maturing process. Rebars can be detached from concrete and air voids are formed, where water or acidic solutions can gather. That process leads to the loosing of adhesion of steel to concrete, which favors cracks appearing around corrupted rebars and construction joints.
4.7. Cracks caused by environmental conditions
Aggressive environment can also cause cracking in the concrete shell. It leads to dampness and carbonation of concrete and steel corrosion, which finally causes swell of the concrete shell. All the above phenomena lead to cracks and degradation of concrete cover.

During wintertime, cracks can propagate due to the increasing volume of frozen water in already existing cracks. Furthermore cracks may be caused as a result of geotechnical works carried out nearby [7].

5. Reasons for the appearance of cracks
There are many mistakes which were made during construction of chimneys:
– too small distances between vertical and horizontal steel bars in concrete wall,
– insufficient concrete care (too rapid drying of the wall, low moisture during an initial maturing period),
– using adjustable formwork,
– using joints in constructing chimneys (improper joint design),
– too long pause between subsequent concrete fillings, without proper preparation of concrete surface connecting old and new layer of the concrete wall,
– using vibrators inappropriate for steel rods diameter and for distances between them (touching steel rods with vibrators),
– too small or damaged thermal insulation,
– damaged moisture protecting coating,
– too much condensate inside the chimney,
– shrinkage caused by rapid drying of concrete
– self-stresses in the chimney wall due to shrinkage,
– too few steel bars used against shrinkage of the chimney wall,
– adding loads onto chimney such as satellite dishes,
– excessive shrinkage of concrete, especially in thick concrete covers,
– shallowly embedded reinforcement rods,
– excessive thermal load i. e.:
– high temperature gradient (local insulation, high temperature in the chimney wall caused by damaged insulation, high amplitude of temperature within every 24 hours),
– too small number of horizontal reinforcement rods in the case of vertical cracks,
– too small number of vertical reinforcement rods in the case of horizontal cracks,
– exceeded shear stresses in the chimney wall,
– buckling of vertical reinforcement rods,
– violation of curing concrete during displacement of formwork,
– corrosion of reinforcement rods,
– water in the cavities surrounding reinforcement rods (cavities created during vibration) of concrete,
– degradation of concrete by chemical smoke condensate, rainwater etc.,
– too high volume of coarse aggregate in the concrete mix
– local imperfections, non-vertical axis of the chimney

6. Conclusions
The phenomenon of cracks in the walls of chimneys is undesirable for concrete constructions. Chimney's walls cracks reduce the rigidity of the structure, reduce the durability of chimneys, change the main stress system in the chimney, increasing shear stress, intensifying corrosion. For this reason, the causes of cracks in the concrete walls of the chimney should be taken into account when designing. During chimneys building and exploitation cracks should be and eliminated [12]. One must notice,
that similar aspects of concrete behavior may be examined in the case of other tall concrete structures like silos [13].

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