Preservation and stability of industrial masonry chimneys

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ABSTRACT: Out of the over 10 000 there once were in the Netherlands, there are now only 600 industrial chimneys left. They should be preserved as a cultural heritage. In this paper, some traditional building features and renovation aspects are mentioned. Additionally the paper discusses the parts, features of and stability checks for industrial masonry chimneys. Due to the tapered hollow tube shape of chimneys, an almost perfect synergy between shape, function and loading is achieved. Checking of the stability of a masonry chimney is similar to checking of the stability for shear walls. The line of thrust can be found by ‘numerical integration’. The M-N interaction curve of a section for a specified ratio between inner and outer radius, is a tool for stability checks. The presented calculations are an illustration of the stability checking procedure for verification vis-à-vis the present codes when renovation of existing chimneys is required.

1 INTRODUCTION

The chimney used to be the symbol of prosperity of a factory. Between the years 1880 and 1960, over 10 000 brick masonry chimneys were built in the Netherlands. Out of these, only 600 remain. Since new chimneys are not made out of masonry anymore, the chimney foundation ‘stichting fabrieksschoorstenen (STIF)’ strives the conservation of the remaining ones, (Havelaar, 2001). Apart from presenting some renovation techniques, this paper discusses the components, characteristics and the stability checks of existing industrial masonry chimneys.

Due to their tapered hollow tube shape, masonry chimneys form an almost ideal synergy between shape, function and loading. The stability checks of masonry chimneys and those of load bearing walls have many points in common, (/NN/, 2003). Using ‘numerical integration’, the position of the line of thrust can easily be established. The axial load-moment interaction curve, which is a tool for assessing the stability, depends on, among other factors, the ratio between inner and outer radius. This curve can be derived using numerical integration.

2 CONSTRUCTION

Industrial chimneys are interesting masonry structures, (Figure 1). Architects often preferred masonry whenever this material harmonized with the materials used in the surrounding. Although the structural principle of chimneys is simple, a few special effects are noteworthy. Well designed and maintained chimneys can last for centuries, (Havelaar, 2001) and (Pistone, 1997). An example is the one in Boxtel, (Figure 1), which dates from 1850. Prominent firms had their chimneys flamboyantly decorated, like the English examples, using motifs and banners in coloured bricks, over sailing courses, and decorated top ends with beautiful copings.

2.1 Parts

The main parts of a masonry chimney are the following: foundation, plinth, shaft, protective lining and top, (Figure 2).
The foundation often starts more than 2 m below the ground surface. Usually, it is a thick, circular plate with a diameter of approximately 1/7 to 1/8 of the total height. These robust dimensions are needed to prevent tension in the foundation. Preferably, chimneys were built remote from other buildings with deep foundations.

The plinth, with a height of 1/6 to 1/4 of the chimney height was often built in a shape that was different from the rising shaft. The plinth was often ornamented flamboyantly (Figure 3). Circular as well as square and octagonal shapes are found. In the plinth, the flue enters and changes its course from horizontal to vertical.

In the plinth, also openings were made to allow for the removal of ashes, cinders and soot. Alongside these openings enough masonry was needed to carry the chimney above which in some cases led to square or octagonal sections.

The shaft of high chimneys is almost always cylindrical. Due to the more smooth shape the wind load for a circular section will be smaller than for an equal sized square or octagonal section. See e.g. Jackson, 1979, page 98. The diameter of a chimney varies between 1/6 and 1/10 of the height and widens downwards, usually with an inclination between 1:60 and 1:40, but 1:50 on average.

The wall thickness of the shaft varies over the height in steps of approximately 50 mm. Parts of the shaft with the same wall thickness are called drums.

To prevent cracking, iron straps with bolted connections were applied around the chimneys. The spacing of the straps was approximately 1/2 to 1/3 of the diameter, and depended, among others, on the expected temperature of the hot gasses and fumes.

Iron climbing stirrups were built in every four or five courses, both along the inside and the outside of the walls. These irons were positioned vertically above each other, preferably on the leeward side of the chimneys, so that they were somewhat protected against the fumes and the weather, figure 2.

The bottom part of a chimney was usually constructed as a cavity wall. The inside wall functioned as a lining protecting the outer load bearing leaf against high temperatures and the prevalent aggressive smoke and flue gasses. Its thickness was often only 100 mm.

The outer leaf was provided with openings at the bottom through which relative cold air was sucked in via the ventilated cavity, which in turn, at a higher level, opened into the main flue chamber (detail Figure 5). Because of this ‘false draught’ the protection lining is cooled. The flue gasses also cooled down at a lower rate, and as a result the chimney has a better draught. For most of the industries it was sufficient to build the protection lining to a height of 1/4 to 1/3 of the height of the chimney.
The top-drum of a chimney was often only 140 mm thick. The top itself on the other hand was often thicker. In some cases steel cables were applied to the top as a kind of reinforcement (Figure 4). The top served to carry rain water away from the masonry. The extra thickness gave it more robustness and ability to withstand the effect of rain and curling smoke. Some extra weight also improves the top's load bearing capacity.

2.2 Materials

In the Netherlands, most of the industrial chimneys were built following the same pattern. Earlier, small sized bricks were used. Head joints were narrow. In this way little brick-cutting was needed to obtain the desired round section. The wall thickness could be reduced more gradually as well. Later, after the invention of the extrusion press around 1900, special radial bricks were developed for round chimneys.

These radial bricks had somewhat rounded sides and holes. A choice of dimensions was available making it possible to make any thickness of wall, in increasing steps of 50 to 70 mm. The popular thickness of radial bricks was 90 mm and the joint thickness, 10 mm. Motifs or banners were made using bricks with a different colour.

The significance of the influence of mortar on the strength and stiffness of masonry is related to the ratio between brick and joint thickness. If thin units and relatively thick joints are used in combination with lime or lime-trass mortar, masonry stiffness is lower. Sirag (1923) highlights the large stiffness of Portland cement mortars and mentions further that mortars of this kind are completely hardened when the chimney is put into action while lime mortars are not yet hardened then, because the hardening process of lime mortars proceeds slower for thicker walls. Old industrial chimneys, built with relatively small bricks of 4 x 8 x 17 cm$^3$, in an era in which the use of Portland cement was not yet popular, were evidently in very good condition, as observed by Sirag, (1923, page 75).

2.3 Renovation

As long as the chimney was in use and provided, the chimney stayed dry, there actually occurred little problems. The layer of soot formed a natural protection for the masonry. Once a chimney is out of use, it deteriorates, (Pistone, 1996), (Havelaar, 2001).

At the top and in the west, predominantly the rain and wind direction, weather action and effects of smoke, gases with Sulphur from burned oil or coal, were severest. Due to rain and radiation of the sun the masonry is alternately dry and wet. This causes the Sulphur to react with the lime in the mortar, changing it to gypsum. Consequently, the masonry in these parts of the chimney, suffer the largest deformations. Sometimes, the mortar is eroded, even to a depth of 150 mm.
In order to preserve a chimney, it is of paramount importance to get and maintain the inside masonry in a perfect condition again. Firstly, loose parts should be removed pneumatically and the masonry cleaned. It must be noted that there is always some of the old mortar remaining for instance, in the holes of the perforated radial bricks. Secondly, it is necessary to counteract the negative action of Sulphur in the mortar, by using a special liquid. Then, the masonry can be repointed using an acid and heat resistant pointing-mortar. Generally, the outer side also has to be cleaned and the joints scratched out and repointed. Renovation works are carried out from a scaffolding made from steel frames. These frames are hung onto the chimney with steel horizontal wires, at a spacing of approximately 1.40 m, Figure 5.

Chimneys may become bent by the expansion of the mortar (Sulphur-reaction), however, the corrosion of the climbing irons causes more damage, while the chimney is tilted towards one side. Bent chimneys are straightened again by jacks, positioned in openings. The masonry above the jacks is lifted. Then the joints are cleaned and filled. After hardening of the filling mortar, the jacks are removed and the openings closed.

Because of their considerable height, chimneys offer attractive positions for placing of dish aerials or advertising boards. These however are often a source of damage. Wind currents, disturbed due to the protruding shape of these elements, may cause some torsion in the masonry. Because masonry is not capable of resisting torsion, this is a very unfavourable load condition.

3 CALCULATION

3.1 Turn over safety

In principle, a chimney is a hollow pipe, rigidly connected to a foundation. The main load is wind. The load causes shear and bending moments and causes the line of thrust to deviate from the vertical axis, schematically represented in Figure 6.

The design calculation may be considered as a check for overturning. The moments caused by wind and out of plumb weights due to leaning are counteracted by the self-weight of the chimney. The resultant of the axial forces N acts at an eccentricity \( e = \frac{M}{N} \). When the moment M is too large, the chimney will overturn, irrespective the masonry strength. Of course, the eccentricity e should be smaller than the outer radius R with a certain safety factor. Vandepitte suggested a safety factor of \( R/e = 2.3 \).

3.2 Axial forces, moments and line of thrust

In order to establish the distribution of axial forces and moments over the height of a chimney, it is divided into sections. The section length was related to the chimney parts that had the same wall thickness, called ‘drums’. Usual, these ‘drums’ were five meters in length, (Sirag, 1923) and (Vandepitte, 1979). Nowadays, with the use of a spreadsheet program, these sections can be much shorter, e.g. 1 m. To establish the values at a certain section \( i \), or the next section \( j \), one meter below, the following formulae can be used successively for \( i = 0 \) to \( n - 1 \):

- \( R_j = R_i + v \) outside radius (1)
- \( r_i = R_i - d_i \) inside radius (2)
- \( A_i = \pi (R_i - r_i)^2 \) section (3)
- \( W_j = W_i + (A_j + A_i) \) weight per drum (4)
- \( \gamma = 18 \text{kN/m}^3 \) specific weight

\( N_j = N_i + G_i \) axial force (5)

\( q_{wi} = R_i \) wind load (6)

\( p_{wi} \) is the value for wind pressure acc. NEN 6790

\( V_j = V_i = (q_{wi} + q_{wj}) / 2 \) shear (7)

\( M_j = M_i + (V_i + V_j) / 2 \) moment (8)

\( k_i = M_i / E_i \) curvature per drum (9)

\( l_i = \pi / 36 \ast (R_i^4 - r_i^4) \) moment of inertia (10)
Figure 6. Schematic representation of wind pressure, N and M versus height, and line of thrust drawn in vertical section over a chimney.

Wind pressure kN/m² vs. height.

Figure 7. Wind pressure versus height.

\[ \varphi_0 = \Sigma i = \ln k_i \] rotation at the top (11)

\[ \varphi_j = \varphi_i - (k_i + k_j) / 2 \] rotation at level j (12)

\[ w_0 = \Sigma i = 1 \varphi_i \] horizontal sway at the top (13)

\[ w_j = w_i - (\varphi_j + \varphi_i)/2 \] horizontal sway, level j (14)

The axial force (N) may easily be determined from the weight of the chimney above a given height. The external and internal radii are a function of the height, keeping in mind that the wall thickness increases downwards in steps of approximately 50 mm.

Wind pressure (pw) varies with height as well, Figures 6 and 7. The values can be taken from current codes, like NEN 6790, which also gives values to allow for the smooth rounded shape of the section. Shear per section and the bending moment can be established per section. As an example, the N and M distribution over the height are plotted in Figure 6a for a chimney of 72 m in height. At the top R = 1.75 m and r = 1.53 m, at the foot R = 2.81 and r = 1.82 m. R and r are the external and internal radii, respectively, of the section under consideration.

For simplicity, all load factors are taken as 1 and only the wind pressure as given in the code, with no correction factors is used. However, the value for pw = 1.57 kN/m² at the top corresponds almost exactly to the value of 1.5 kN/m² used in Sirag (1923). The position of the line of thrust can be found by calculating the eccentricity e = M/N in every section. Figure 8b shows the ratio e/R between eccentricity and out side radius which can be useful for checking stress.

The curvature (ki) of each drum can be calculated with formula (9), using the method of the reduced moment surface, while \( k_i = M_i/E_i \), formula (9) and by summation the rotation (\( \varphi \)) and the displacement (w) of the centre of gravity of each section can be found. The moment of inertia, formula (10), holds for an uncracked section. Usually, extrusion wire cut bricks and a lime mortar have been used. With a common brick thickness of 90 mm and a bed joint of 10 mm the modulus of elasticity, (E) ranges between 8000 and 12 000 N/mm², (Sirag, 1923).

3.3 Stress distribution over a section

In the following stress distribution calculations it is assumed that the masonry cannot resist any tensile stresses. Further the hypothesis of Bernoulli/Navier, plane sections remain plane, is used. Applied stresses in uncracked sections may be determined using

\[ \sigma = \frac{N/A \pm M \cdot z}{I} \] (15)

When tension occurs the section will crack, i.e. when the stress \( \sigma \) at an edges becomes positive. Then the
The eccentricity is approximately equal to 1/9 to 1/10 of the diameter, depending on the wall thickness.

The neutral axis, where stresses are zero, is the boundary of the cracked part of the section. At the other side the stress is maximal, and in between, a bi-linear stress distribution like the one given in NEN 6720 may be assumed. Figure 9 gives a schematic diagram of the stress distribution. On a cracked section the value and position of the resulting axial force of the assumed stress distribution can be determined using numerical integration. The cracked section is divided into strips and per strip the resulting force $F_i$, is estimated and its contribution to the moment, $M_i$, computed, using the distance ($y_i$) of $F_i$ to the line through the center of gravity and formula (16) and (17).

$$\Delta F_i = A_i \cdot \sigma_i$$  \hspace{1cm} (16)

$$\Delta M_i = A_i \cdot y_i$$  \hspace{1cm} (17)

Next, both $N$ and $M$ are calculated with:

$$N = \frac{\sum \Delta F_i}{n} \hspace{1cm} (18)$$

$$M = \frac{\sum \Delta M_i \cdot y_i}{n} \hspace{1cm} (19)$$

At this stage, for the assumed crack depth, the values of $N$ and $M$ as functions of the compressive strength $f'_{mod}$ are known, as $\sigma_i$ is a function of $f'_{mod}$. The next step is to express the values of $N$ and $M$ as dimensionless ratios, thus the utilisation ratio ($\nu$) and the moment capacity ($\mu$) as follows:

$$\nu = \frac{N}{N_{\text{max}}}$$  \hspace{1cm} (20)

$$\mu = \frac{M}{M_{\text{in}} (N_{\text{max}} \cdot R)}$$  \hspace{1cm} (21)

The procedure is repeated for a number of crack depths for the section under consideration with a predetermined wall thickness/radius ratio, e.g. $R/r = 0.6$. Subsequently, the whole process may be repeated for other $R/r$ ratios.

In Figure 9 the relationships between $\mu$ and $\nu$ for three $R/r$ ratios are plotted. This graph serves as a tool for the determination of the working stresses.

For comparison, the more familiar values of a rectangular section, using a bi-linear $\sigma$-$y$-diagram, are also plotted. For each section and each crack depth the position of the compressive stress resultant (eccentricity) is known, while

$$\frac{e}{R} = \frac{M}{(N_{\text{max}} R)} = \frac{\mu}{\nu}$$  \hspace{1cm} (23)

The ratio $\frac{e}{R}$ is plotted against the utilization ratio in Figure 11, crack depth versus $\nu$ in Figure 12.

### 3.4 Checking stress

For checking stress, the eccentricity ratio ($e/R$) at every height due to the loading may be deduced from Figure 8b. Using the result in Figure 11 the extent to which the section is cracked for this eccentricity may be found and the values for $\nu$ and $\mu$ can be determined. When these two values are known, the working stresses at the section being considered can be calculated. It was advised by Sirag, 1923, to keep the working stresses small since the masonry of the chimney could be exposed to high temperatures and the wind loading could cause a certain fatigue.

When linear-elastic behaviour is assumed, some reserve strength is available. For a hollow tube shape this reserve strength is even greater than that of a rectangular section. Besides the working stresses the crack depth should be considered. According to Sirag,
1923, in everyday use, the crack depth should be less than the wall thickness. This prevents false draught via cracks which would occur if the crack touches the inner circumference. In the ultimate situation crack depths should be less than 0,6 times the outer diameter for chimneys higher than 60 m. For shorter chimneys the crack depth may be a little larger, Sirag 1923. For a topple over safety factor of 2, the eccentricity equals 0,5 R, \( \nu \sim 0,5 \) (fig. 11) and the crack depth, 0,22 R (fig. 12). The value of \( \mu \) (M/Nmax/R) equals 0,25, Figure 10. 

### 3.5 Additional effects

Besides wind as the main load, additional loads such as effects of leaning, one sided heating from the sun, second order effects and resonance should be considered. These loads will cause additional lean of the chimney. As a precaution, it is recommended that, in design, chimneys should be considered to be out of plumb by 1/250 of their height, (Sirag, 1923) and (Vandepitte, 1979). The sun may warm one side in excess of 20°C more than the other side, causing the chimney to bend. Then, the curvature for a drum of 1 m high can be found using:

\[
ki = \frac{1}{2} \alpha \Delta t/Ri, \tag{24}
\]

Off course, second order effects may not be neglected. The position of the centre of gravity of each section was already established, and, in addition, the additional moment can be found using \( \Sigma wi \) which is the sum of the displacement at level i due to wind loading, leaning, rotation of the foundation and other effects, as follows:

\[
\Delta M2i = \Sigma wi * Ni \quad \text{additional moment} \tag{25}
\]

\[
M2j = M2i + (\Delta M2i + \Delta M2j)/2 \tag{26}
\]

These moments would cause a displacement of the centre of gravity of each section and consequently an additional moment from the weight of the chimney above each section.

The effects of resonance are usually checked by considering the deformation that would occur if the weight of the structure would act as a load in the direction of resonance. The weight of each drum has been established earlier to find the axial force, and in a similar way as used for wind loads, the displacement for each section can be established. Then the natural frequency for masonry chimneys can be estimated with:

\[
N = \frac{3}{\pi H^2} \sqrt{\left(\frac{2EI}{5m}\right)} \tag{27}
\]

where \( N \) = natural frequency, \( H \) = height and \( m \) = mass per meter in height. Then the wind speed for this frequency that would cause oscillation can be found using:

\[
V = ND/S \tag{28}
\]

with \( V \) = critical wind speed, \( D \) = chimney diameter in meters (\( D = 2R \)) and \( S \) = Strouhal number, which is 0.23 for round chimneys. The resulting critical wind speeds are usually quite low, (<10 m/s).

The natural damping of masonry provides more than sufficient prevention of oscillation, (Vandepitte, 1979).

When a chimney is in use, there will be temperature gradients between the inside and outside of the chimney, resulting into differential expansion. Radial and transversal stresses will occur. The transversal stresses will be suppressed by the stresses due to the self-weight of the chimney. However, these stresses may cause cracks at the top. In the radial direction horizontal tensile stresses will develop at the outside. In Vandepitte, (1997), a tensile stress of 2,17 N/mm² is calculated for a temperature gradient of \( \Delta T = 80^\circ C \) over the outside wall of the shaft. This stress is usually in the order of magnitude of the tensile strength of the bricks used. Therefore, it is not so surprising that most of the chimneys have vertical cracks. Bending stresses due to gas pressures in the chimney are usually small, even though they are highest in the top part of the chimney.
4 CONCLUSIONS

Chimneys are structures that get their load bearing capacity from their own weight. In principle, design calculations are based on stability checks. The top appears to be the most vulnerable part due to weather influences and the relatively small effect of self-weight.

The $\mu$-$\nu$ (utilisation ratio/moment capacity)-diagram, as a tool for the determination of the working stresses, has a more favourable curve than the diagram for rectangular shapes.

In some cases, crack depth is larger than wall thickness, however, strength is the most important criterion.

The calculations presented here are especially meant as an example of the stability checks for existing chimneys that are to be renovated where verification with contemporary codes is desired. Such checks may be needed if some alterations are to be made, such as the mounting of a dish aerial or an advertising board.

When a chimney no longer satisfies the criteria, the chimney should be modified. The importance of the prevailing axial force is obvious.

Today, industrial chimneys are industrial monuments, which should be treated with respect. After all, they are the silent and some times smoking witnesses of our rich industrial heritage.

REFERENCES