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Structural behaviour under wind loading of a 90 m steel chimney

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Abstract. This paper presents results from an investigation of the structural behaviour of a very slender 90 m high steel chimney erected at Växjö in southern Sweden in 1995. The chimney is equipped with a mechanical friction-type damper at the top. Due to a mistake during erection and installation of the chimney the transport fixings of the damper were not released properly and the chimney developed extensive oscillations in the very first period of service. This caused a great number of fatigue cracks to occur within a few months of service. After the functioning of the damper had been restored and the fatigue cracks were repaired an extensive program was initiated in 1996 to monitor the structural behaviour of the chimney under wind loading. In the investigation data were collected for more than six years of continuous measurements and regular observations of the chimney. The data obtained have some general relevance with respect to wind data, behaviour of a slender structure under wind loading, and the effect of a mechanical damper. Also some theoretical studies were performed as part of the investigation of the chimney.

Keywords: full scale measurements; cross wind oscillations; vortex shedding; chimney; mechanical damper and dynamic wind loading.

1. Introduction

During the winter period of 1995/1996 serious cracks were reported for several chimneys in northern Europe (Tranvik and Alpsten 2002, Dyrbye 1997). One of them was the VEAB steel chimney, located at the VEAB district heat and power plant at the town of Växjö in southern Sweden. During the winter period witnesses observed oscillations with an estimated top amplitude deflection of about half the diameter for up to some hours at a time.

A description of the VEAB chimney, the data recording system, behaviour of the mechanical damper, recorded dynamic properties of the chimney, observed wind properties, recordings of deflections and strain-gauge measurements and first and second mode oscillations has been given in a separate report (Tranvik and Alpsten 2002) and is summarised in this paper.

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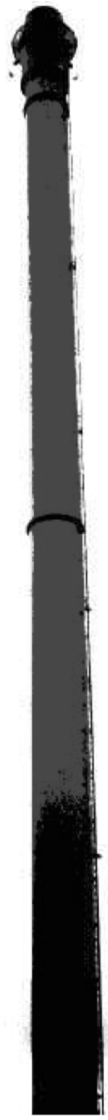


Fig. 1 Top half of the VEAB chimney

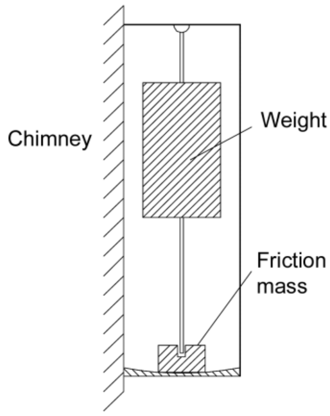


Fig. 2 A mechanical pendulum damper as used at the VEAB chimney (schematically). The damping is achieved by a friction mass that slips on a bottom steel plate

2. Description of the chimney

The VEAB chimney has the following overall data:

Height	90 m
Outer diameter of structural shell	2.3 m
Diameter of inner pipe	2.0 m
Thickness of inner pipe	3 mm
Outer diameter of top portion with Damper	2.8 m

The thickness of the structural shell varies from base where $t = 18$ mm to top where $t = 6$ mm. The total mass of the chimney is 79500 kg including the damper. For structural parts weather-resistant steel with yield strength of 355 MPa is used.

The VEAB chimney is equipped with a mechanical pendulum damper at chimney top to reduce vortex shedding oscillations (Fig. 2), an inner pipe and an outside ladder. An insulation is placed between the outer shell and the inner pipe.

The mass of the damper pendulum weight is 1246 kg, that is, 1.6 percent of the chimney weight. The optimum damper frequency tuning $f_{e2} = \{1/(1+0.1)\} \cdot f_{e1} = \{1/(1+0.1)\} \cdot 0.288 = 0.262$ Hz (Hans Ruscheweyh 1982) where f_{e1} is the lowest measured natural frequency. The three lowest modes of natural frequency were calculated to 0.282, 1.44 and 3.86 Hz. The observed natural frequency of first mode vibrations was found to be 0.288 Hz in repeated observations.

The initial design calculations did not meet the Swedish codes concerning slenderness ratio (height over diameter) and limits for top amplitude deflection during vortex shedding (BSV 97 1997). For the VEAB chimney the slenderness ratio is 39, as compared to the limit value of approx. 30 for applying the design model for vortex shedding in the code (BSV 97 1997). This limit is based on data for some very slender chimneys, see further discussion below. Some other codes, such as DIN 4133 (1991) and Eurocode 3 (1997), do not specify such limits.

The mechanical pendulum damper of the VEAB chimney was found to be malfunctioning and was adjusted in September 1996 and the cracks were repaired.

3. Data recording system

Because doubts remained about the reliability of the damper even after the adjustment it was decided that oscillations of the structure should be monitored. The data recording system used consists of three parts, the strain-gauges, the wind data transmitter and the computer. The data recording system was created primarily for studying the influence of first mode oscillations with respect to fatigue strength. Field recordings have been made continuously for more than six years (1997 through 2002).

4. Behaviour of the mechanical damper

Tests were performed to determine the damping properties of the VEAB chimney, that is, the logarithmic decrement of the chimney with the mechanical damper (Table 1 and Fig. 3). The chimney was initially forced to deflect and the resulting free sway of the chimney was recorded. Comparison tests were made for the chimney with the mechanical damper in a locked position.

The damping test was repeated 20 times in order to get a good average value of the logarithmic decrement, and to get some understanding of the variability in the damping properties.

The damping tests were made in August 1997 in fairly calm weather. The wind velocity was below 6 m/s (10-minute average) during all tests performed. Care was taken to avoid influence of aerodynamic damping from gust wind during the damping measurement.

The variation in the logarithmic decrement obtained in the repeated tests, expressed as a standard deviation of about 0.01, could be due to at least three reasons, listed here in the order of estimated importance:

Table 1 Conditions and results from 20 tests of damping of VEAB chimney

Test #	Time of test	Initial deflection range (mm)	Wind velocity (m/s)			Wind direction (degrees, 0/360)			Number of oscill. k	Logarithmic decrement $\delta_{ave\ k}$
			10 s	1 min	10 min	10 s	1 min	10 min		
Chimney with mechanical damper in normal operation, date 1997-08-05										
1*	11.22	376	8.0	6.5	5.3	194	161	159	6	0.072
2**	12.55	304	5.0	4.7	2.9	168	172	118	7	0.064
3	13.04	425	4.5	6.4	4.8	179	170	173	10	0.057
4	13.30	419	7.2	6.7	5.7	160	172	163	8	0.070
5	13.34	422	5.2	5.7	5.6	173	169	164	9	0.062
6	13.38	394	4.9	6.2	5.6	136	152	162	6	0.098
7***	13.41	382	6.3	4.8	5.6	156	154	164	6	0.081
8	16.45	507	4.3	3.6	3.1	181	187	169	12	0.065
9	16.55	415	3.3	3.7	3.3	219	191	184	10	0.068
10	16.59	411	4.3	3.5	3.4	170	193	186	7	0.070
11	17.01	421	3.7	3.8	3.5	168	172	185	7	0.078
12**	17.04	445	2.3	3.1	3.5	171	172	182	9	0.068
13	20.31	445	3.6	2.9	2.5	170	169	172	10	0.063
14**	20.36	426	1.9	2.7	2.7	185	173	172	6	0.068
15	20.40	397	3.4	2.7	2.8	157	165	170	8	0.068
16**	20.44	382	2.7	3.3	3.1	168	155	164	7	0.071
Mean					4.0			168		0.070
Standard deviation										0.009
Chimney with locked mechanical damper, date 1997-08-06										
17	10.55	184	2.9	3.6	3.6	195	182	172	4	0.038
18	10.58	202	2.4	2.5	3.8	210	191	175	9	0.031
19	11.04	191	4.8	5.8	3.9	184	182	175	5	0.056
20	11.09	185	3.7	3.3	3.9	137	131	170	3	0.048
Mean					3.8			173		0.043
Standard deviation										0.011

Notes to table:
*A technician was standing on the platform at the top of the chimney during the test.
**During the course of oscillations one or two irregularities were obtained. These oscillations were disregarded in determining the mean logarithmic decrement $\delta_{ave\ k}$ given in the table.
***The pulling nylon rope fractured near the top of the chimney instead of at the other end.

1) Accidental variations in the action of the mechanical damper
2) Disturbances from variations in environmental conditions, mainly aerodynamic damping due to variations in wind velocity and wind direction, due to the fact that these tests were made under field conditions
3) Inaccuracies in the recording system.

The recorded logarithmic decrement of the VEAB chimney with the mechanical damper in normal operation is 0.070, that is, the mechanical damper increases the normal upper limit of 0.03

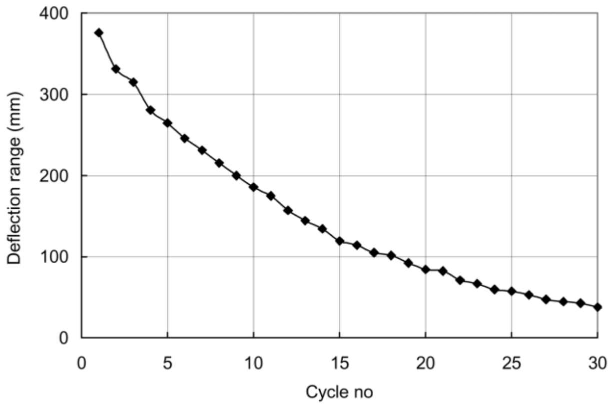
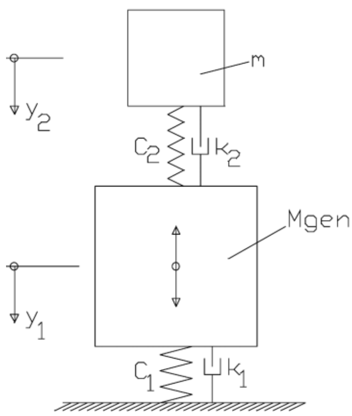


Fig. 3 Deflection range as a number of time (cycle number). Test no 1 with mechanical damper in normal operation. One cycle corresponds to approximately 3.5 s



$$M_{\text{gen}}\frac{d^2y_1}{dt^2}+c_1\cdot y_1+c_2\cdot(y_1-y_2)+k_1\cdot\frac{dy_1}{dt}+k_2\cdot(\frac{dy_1}{dt}-\frac{dy_2}{dt})=F\cdot\sin(\omega\cdot t)$$

$$m\cdot\frac{d^2y_2}{dt^2}+c_2\cdot(y_2-y_1)+k_2\cdot(\frac{dy_2}{dt}-\frac{dy_1}{dt})=0$$

M_{gen} = Generalised mass of the chimney
m = Damper pendulum mass
F = Amplitude for vortex shedding force
y_1 = Deflection of chimney
y_2 = Deflection of pendulum mass
c_1 = Chimney stiffness
c_2 = Damper stiffness
k_1 = Chimney damping
k_2 = Damper damping
v_1 = Velocity for M_{gen}
v_2 = Velocity for m
a_1 = Acceleration for M_{gen}
a_2 = Acceleration for m
ω = Angular frequency of vortex shedding

Fig. 4 Model of a two-mass spring and damper system

to be used in design (BSV 97 1997) by a factor of 2.3.

For the chimney with locked damper the recorded logarithmic decrement is 0.043. This value is somewhat higher than the range 0.02 to 0.03 to be used for design of normal steel chimneys with installations in the form of internal ducts, ladder etc. One reason for the recorded value being higher than this range might be more-than-usually efficient damping from non-structural elements or some unintended action from the locked damper.

A theoretical study of the two mass spring-damper model has been performed (Fig. 4). Ruscheweyh has presented a simplified calculation model for a chimney provided with a tuned pendulum mass damper (Fig. 4, Ruscheweyh 1982). In that model, damping from the mass

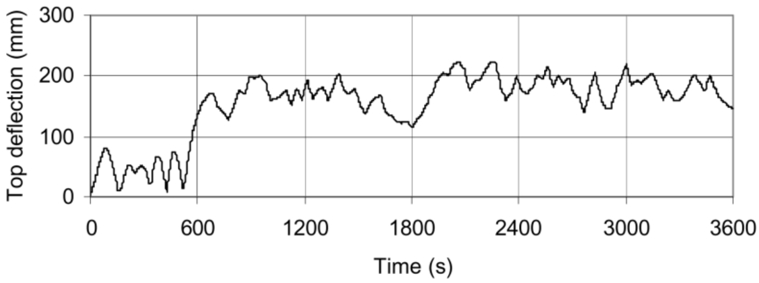


Fig. 5 Simulated time history of top amplitude deflection (functioning damper) at the vortex shedding frequency $f = 0.357$ Hz, a 50 percent randomised vortex-shedding frequency and force.

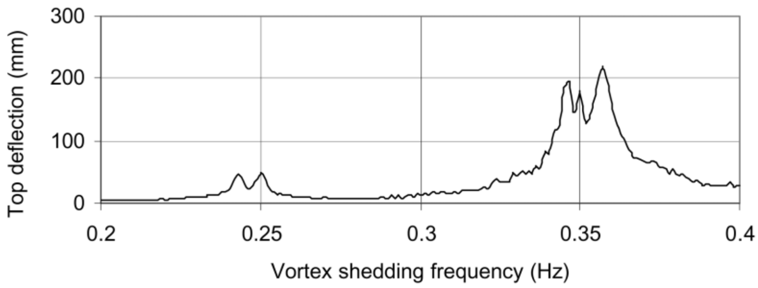


Fig. 6 Simulated dynamic response of top amplitude deflection during vortex shedding and a tuned functioning damper. Both vortex shedding frequency and critical wind velocity during vortex shedding were randomised to 50 percent

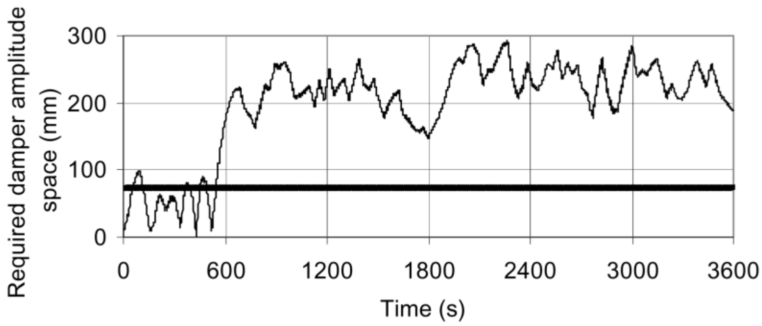


Fig. 7 Simulated time history of required free functioning damper amplitude space at the vortex shedding frequency $f = 0.357$ Hz, a variable vortex shedding force and tuned frequency $f_2 = 0.262$ Hz. Both vortex shedding frequency and critical wind velocity during vortex shedding were randomised by 50 percent. The horizontal line shows available damper space in the actual chimney, 75 mm

damper k_1 was neglected. That model has been extended in the present investigation to account also for the effect of the mass damper k_1.

The results of the study showed that the VEAB chimney damper house will not allow the necessary oscillation movement. The space in the damper house is limited and the pendulum mass angle movement is therefore limited to approximately 1.2 degrees. The maximum possible relative amplitude movement in horizontal direction is 75 mm. This may explain the surprisingly low damping value delivered by the damper unit. A reasonable assumption is that the damping action observed was achieved by a combination of the limited pendulum movement (Fig. 7), the stroke of the damper friction and/or pendulum mass against the vertical damper unit walls and the energy losses in the chain movements. The damping measurements and the theoretical study were in good agreement. Therefore the model developed can still be used for at least quantitative considerations.

In Fig. 5 a simulated history of top amplitude deflection for a functioning damper is shown. The dynamic response is shown in Fig. 6.

The critical velocity 3.24 m/s corresponds to a natural frequency of 0.282 Hz, which is used in Figs. 5 and 6. Maximum top amplitude deflection was then shown to be 0.220 m at a vortex shedding frequency 0.357 Hz, equivalent to a wind velocity of 4.1 m/s (determined for a Strouhal number of 0.2).

Because of lock-in phenomena the amplitude could increase considerably because the vortex shedding starts at lower wind velocities, and the chimney continues to oscillate with the same frequency as the vortices were separated from the chimney. It is well known that the Strouhal number could be reduced to half its normal value because of lock-in effects. The wind velocity will be doubled and the wind pressure increases by a factor of four. Slender structures are more sensitive for lock-in phenomena, see for instance (Alpsten 1985). The probability for conditions causing this type of lock-in is low, but during a long life-time of a chimney it should be considered. Therefore special lock-in phenomena could be dangerous for very slender chimneys. This is the reason for the limitation of the applicability of the equivalent load in BSV 97 (1997).

5. Recorded dynamic properties of the chimney

A typical time history response during vortex shedding was an immediate increase from small deflection ranges to loads of large deflection ranges (Fig. 8). The large deflection ranges continue for typically about 100 seconds and decrease immediately again. The deflection direction was almost perpendicular to the wind direction. This supports the thesis that the recorded oscillations were primarily of vortex-shedding type.

It was also obvious that large deflection ranges occur even if the turbulence intensity of the wind velocity was relatively large. The 10-min average values seem to be most important for vortex shedding, that is, action of short period of time is of less significance.

Once during the recording period a vortex shedding behaviour with a long period of huge top deflections has been observed as shown in Fig. 9. In the theoretical study it was assumed that the critical wind velocity is 3.24 m/s and the range will be about 440 mm according to Fig. 5.

There could be several reasons for the difference between the results from the theoretical study (440 mm) and the recorded data (650 mm) according to Tranvik and Alpsten (2002). In the theoretical study there was no consideration taken to lock-in effects. But it was obvious that the theoretical model predicted the chimney behaviour reasonably well as may be seen from comparing Figs. 7 and 8 or Figs. 7 and 9.

As may be observed in Fig. 9, the wind velocity turbulence was low and the wind direction was unusually constant during the half-hour in question.

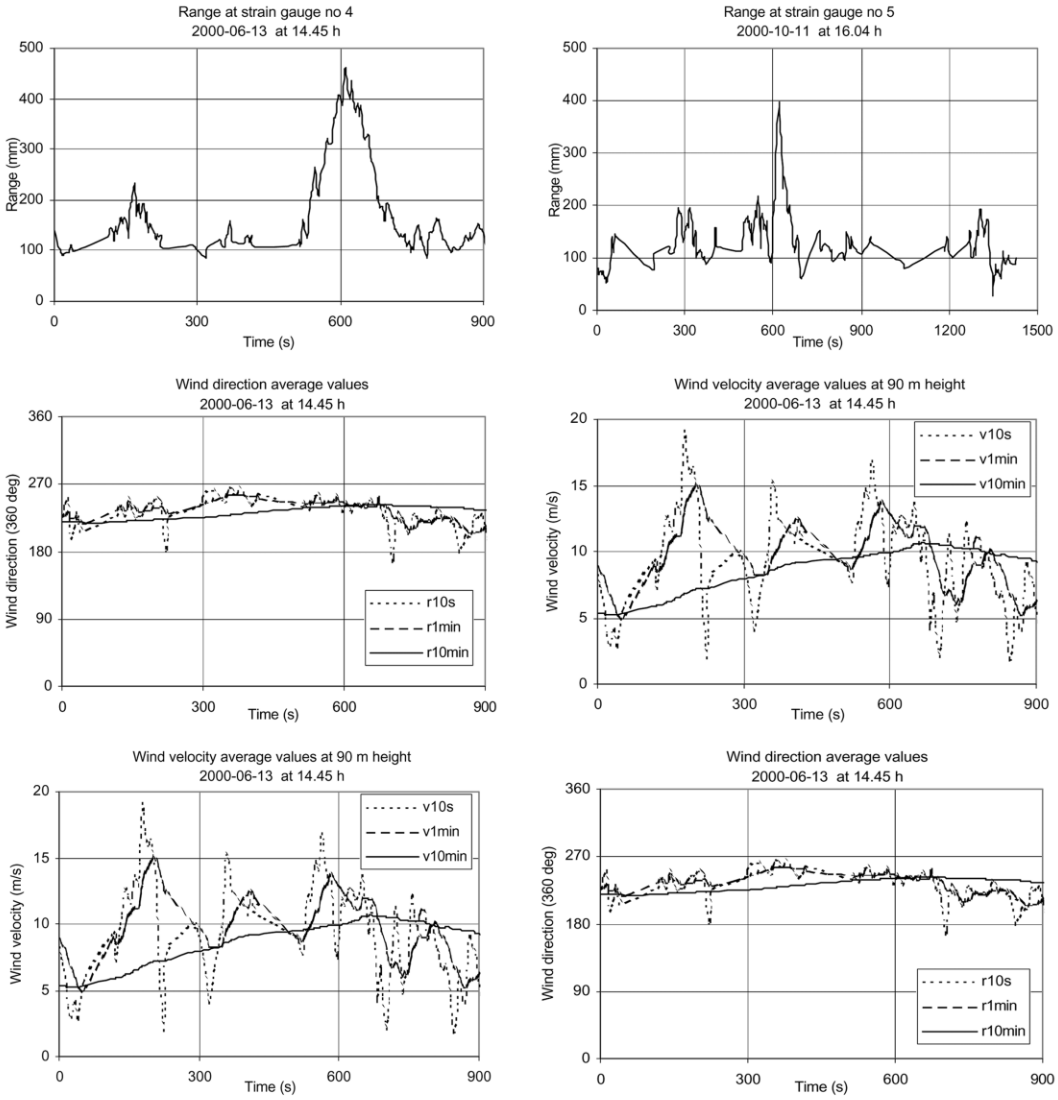


Fig. 8 Typical vortex shedding behaviour for a long period to the left and for a short period to the right with large deflection ranges. Range, wind velocity and wind direction were plotted as a function of time. Wind velocity and wind directions were evaluated as mean values over 10 seconds, 1 minute and 10 minutes

6. Observed wind properties

Dynamic wind pressure may be expressed as $p_{dyn} = 0.5 \cdot \rho_{Air} \cdot v_{10\,\mathrm{min}}{}^2$ where $v_{10\,\mathrm{min}}$ is mean wind velocity over 10 minutes and ρ_{Air} is air density based on daily mean values for temperature. All recorded data for the four years 1997 through 2000 are read, sorted monthly, calculated and finally plotted in anthill diagrams. In Figs. 10 and 11 two typical anthill diagrams are shown for a summer and a winter month.

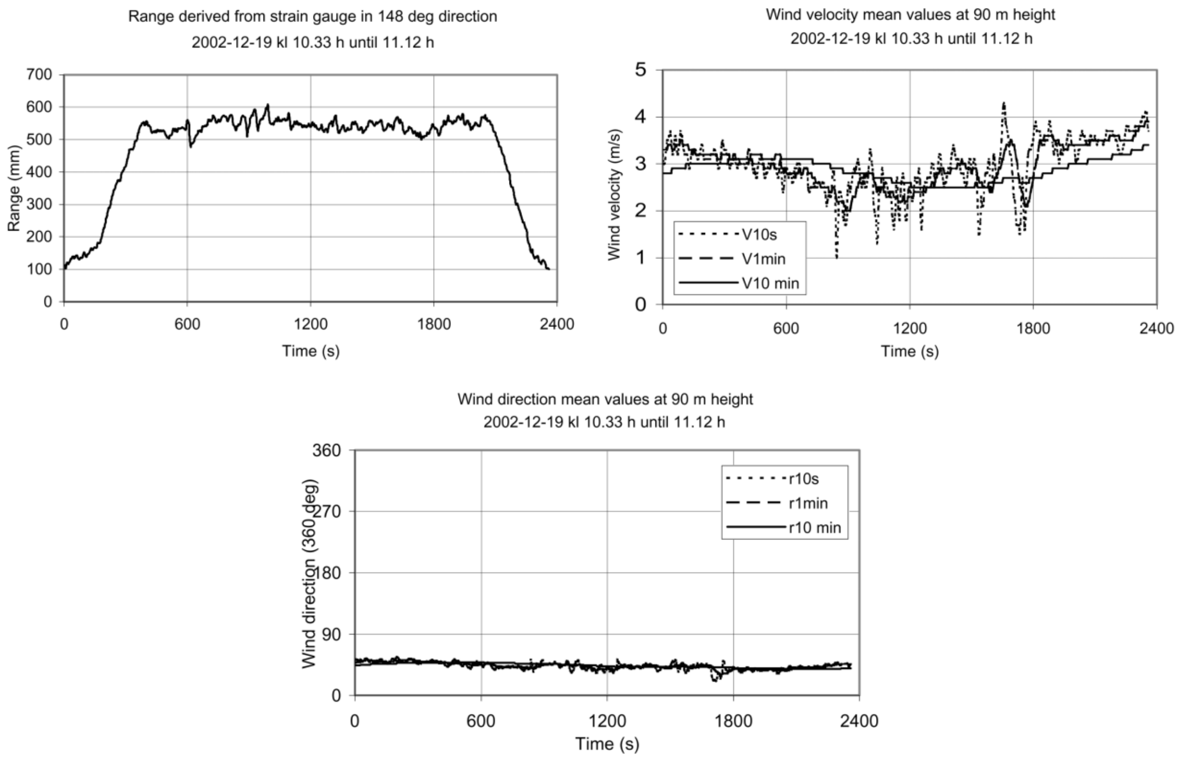


Fig. 9 Vortex shedding behaviour at 2002-12-19 10.33 h through 11.12 h. Range, wind velocity and wind direction were plotted as function of time. Wind velocity and wind direction were evaluated as mean values over 10 seconds, 1 minute and 10 minutes

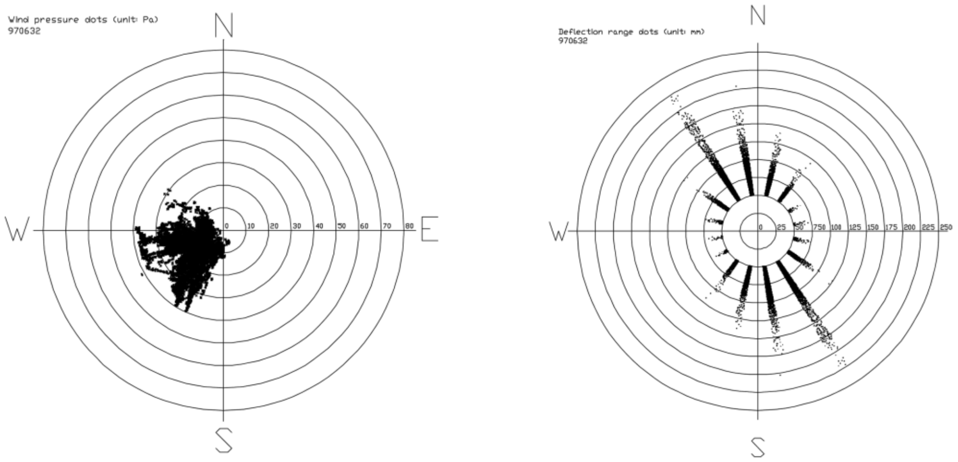


Fig. 10 Anthill diagrams for wind pressure (left) and chimney top deflection range (right), for a typical summer month (June 1997)

Typically the wind direction was perpendicular to the direction of the maximum top deflection of the chimney. Thus the majority of chimney oscillations were of vortex-shedding type.

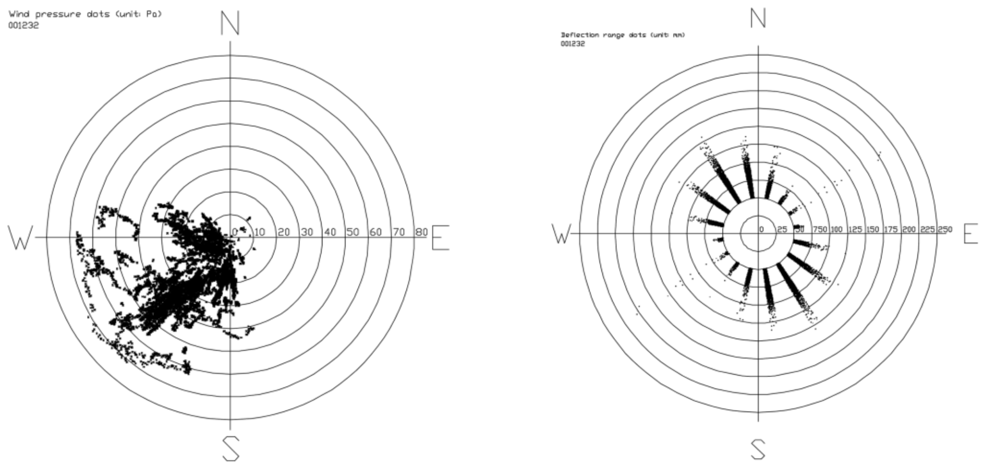


Fig. 11 Anthill diagrams for wind pressure (left) and chimney top deflection range (right), for a typical winter month (December 2000).

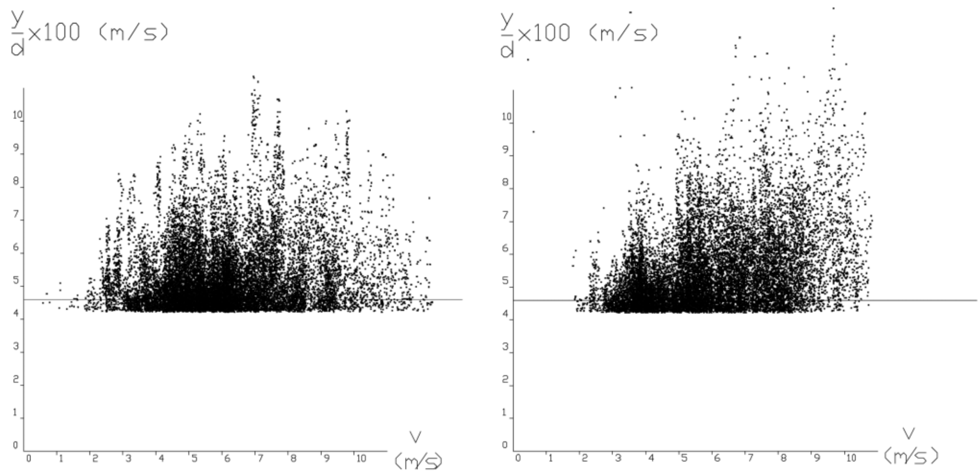


Fig. 12 Maximum top deflection range as a function of wind velocity for a typical summer month (June 1997, left) and a typical winter month (December 2000, right)

Maximum top deflection range plotted in anthill diagrams for two typical months are shown in Fig. 12.

In Fig. 12 10 min mean values are shown for wind velocity. Horizontal axis is wind velocity in m/s and vertical axis is 100 times top deflection range divided by diameter. The horizontal line corresponds to the limit of applicability of the equivalent load-model for vortex shedding given in BSV 97 (1997). As appears from Fig. 12 and is evident from the original data (Tranvik and Alpsten 2002) vortex shedding action is locked in at wind velocities even much above the critical wind velocity. This corresponds well with some previous results (Alpsten 1985).

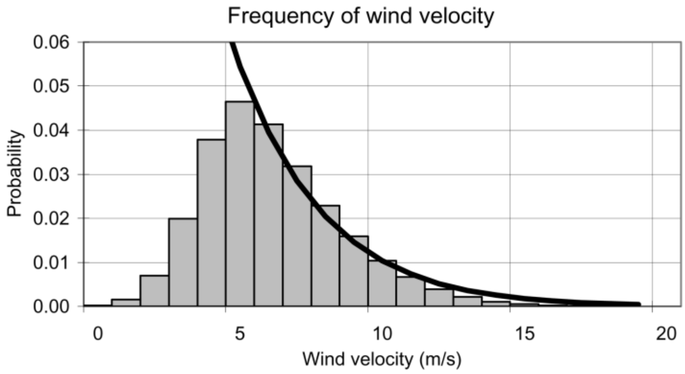


Fig. 13 Histogram for wind velocity, 10 min wind velocity mean value. A Weibull frequency distribution (parameters $\alpha = 1.1$ and $\beta = 3.3$) is fitted to the relevant right part of the diagram

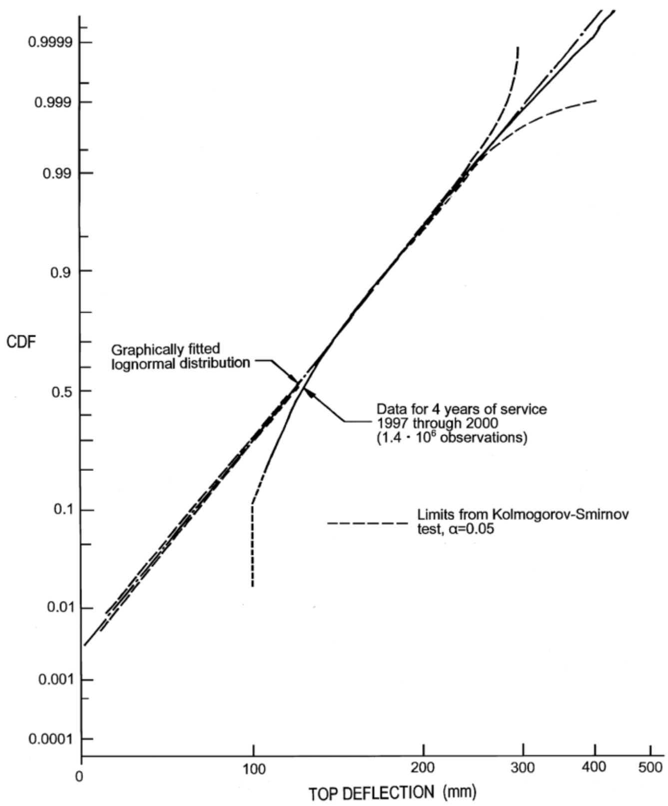


Fig. 14 Cumulative frequency of top deflection range for four years of service 1997 through 2000, derived from strain-gauge recordings in 170-degree direction

7. Frequency of wind velocity

The frequency distribution of wind velocity for the recording period 1997 through 2000 is plotted for 10 min mean values in Fig. 13. A Weibull distribution is fitted to the frequency distribution, but because recorded top deflection ranges below 100 mm were truncated the fitted distribution deviates in the lower range of diagram.

In Fig. 14 a cumulative frequency distribution of top deflection range for four years of service 1997 through 2000 is shown. A log-normal distribution, chosen here for simplicity, was fitted graphically to the relevant upper part of the diagram, and limits from a Kolmogorov-Smirnov test ($\alpha = 0.05$) are plotted.

8. Recordings of deflections and strain-gauge measurements

From the recorded data calculations were made, the data sorted and load spectra plotted, see Fig. 15. As is evident from most curves in Fig. 15, and in particular the curve for the complete six-year period 1997 through 2002, the spectra follow closely a linear relationship in this log-linear representation.

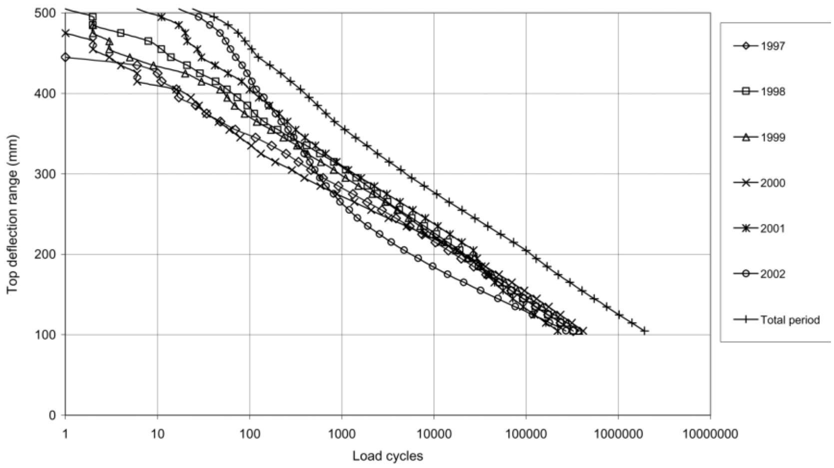


Fig. 15 Spectrum for top deflection range for six years of service 1997 through 2002 derived from strain-gauge recordings in 170-degree direction (approximately in the south direction)

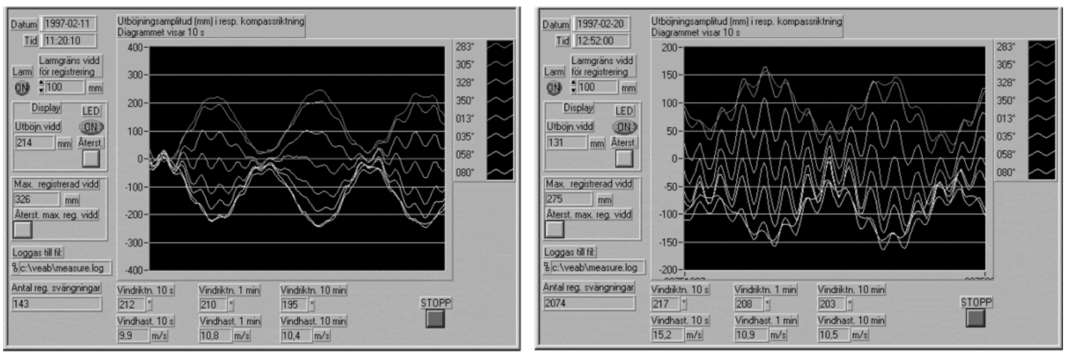


Fig. 16 The virtual instrument for recording and supervising the behaviour of the chimney

9. First and second mode oscillations

Normally oscillations of the VEAB chimney are in the first mode. However at rare occasions second-order oscillations are superimposed of the first order oscillations, as exemplified in Fig. 16.

The observed natural frequencies of the VEAB chimney were found to be 0.288 Hz for the first mode and 1.45 Hz for the second mode. This was in good agreement with theoretical values.

For the first mode recorded results sometimes resulted in a Strouhal number as low as 0.06. The effect explaining this is lock-in, where the vortex shedding starts at the critical wind velocity and continues at increasing wind velocity. This effect is considerable for a slender steel chimney. The results obtained for the VEAB chimney support the slenderness and deflection limits for applicability of the equivalent loads for vortex shedding in BSV 97 (1997). The main problem with creating a code design model valid also for very slender structures (slenderness greater than about 30) is the limited amount of recorded data.

Second mode natural frequency oscillations are seldom observed for steel chimneys. For most steel chimneys only the first mode of natural frequency is of importance for vortex shedding induced oscillations. The high slenderness of the VEAB chimney explains the relatively frequent and large second mode oscillations.

A damper applied at the chimney top has only a limited efficiency for second order as compared to first order oscillations.

10. Codes

Rules for designing slender structures under wind loading as chimneys are found in various codes. Most countries have their own national codes but organisations such as CEN and Comité International des Cheminées Industrielles (CICIND) have developed common codes as the Eurocode and the CICIND code.

There are great deviations between various national codes as well as the common codes. Most codes deal with static and gust wind loads in a similar way. However action from vortex shedding is treated in different ways. The Swedish code limits the allowable slenderness ratio (height/diameter) to max. about 30 for applicability of the structural model in the code (BSV 97 1997). Limit restrictions for the top deflection at vortex shedding are also given.

There is a discussion going on about the need for revision of the codes. See for instance Tranvik and Alpsten (2002) and Verwiebe and Burger (1998).

For static design the 50-year maximum wind load (gust included) considering global and local buckling and plasticity are applied combined with dead load and other loads.

Fatigue effects have to be considered, including effects due to gust wind, vortex shedding and ring oscillations (ovalling).

As a complement to the codes, handbooks have to be used for evaluation of buckling modes, welds and details. In most cases also a finite element (FEA) computer program is necessary for calculating natural frequencies and stress concentrations with an acceptable accuracy.

11. Comparision between some codes and behaviour of the VEAB chimney

The following abridgements in Figs. 17 and 18 are used:

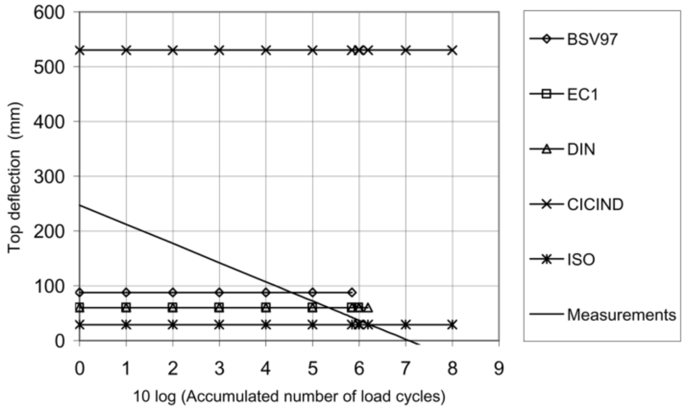


Fig. 17 Spectra for top deflection per year and a functioning damper. Codes discussed in previous sections as well as results from measurements during the recording period 1997 through 2000 are plotted. DIN and EC1 spectra coincide

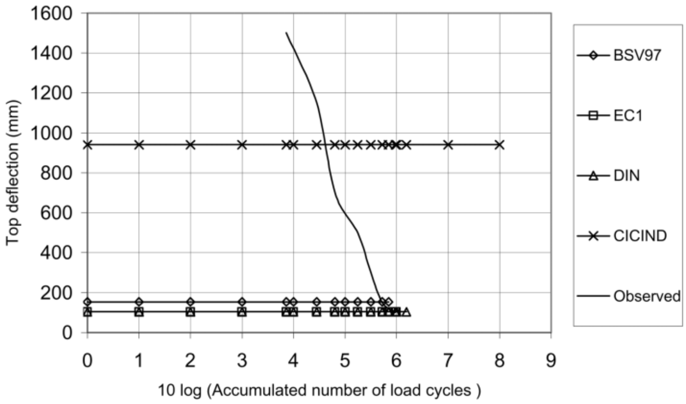


Fig. 18 Spectra for deflection per year and a mal-functioning damper. Codes discussed in previous sections as well as results from the recording period 1997 through 2000 are plotted. "Observed" in the legend means that the data were estimated from observations from some witnesses. DIN and EC1 spectra coincide. ISO is not valid for the conditions with mal-functioning damper

BSV 97	Snow load and wind action (BSV 97 1997)
EC1	Eurocode 1 (Eurocode 1 1994)
DIN	DIN 4133 (DIN 4133 1991)
CICIND	CICIND (Claës Dyrbye and Svein O Hansen 1997)
ISO	ISO 4354:1997 - Wind actions on structures (ISO 4354 1997)

For the functioning damper, Fig. 17 shows that only the CICIND code is safe to use for calculating top deflection due to vortex shedding. For the mal-functioning damper (Fig. 18), no code is safe calculating top deflection.

Both BSV 97 and ISO 4354 have limitations for their use and do not cover the actural properties of the VEAB chimney. Especially the limitations in ISO 4354 point out that the VEAB chimney operates in or in the neighbourhood of an unstable vortex shedding region. The geometric properties of the VEAB chimney had been different from the actual geometric properties if one of the BSV 97, CICIND or ISO codes had been followed strictly.

The results from Fig. 17 and 18 are of great interest since they show that several codes are non-conservative for very slender steel chimneys ($h/d \gtrsim 30$). This is confirmed by the large number of steel chimneys with fatigue cracks in Europe designed according to some of the codes referred to in Fig. 17 and 18 (Dyrbye and Hansen 1997).

There is a need for revision of the structural model to estimate the response caused by vortex shedding of very slender chimney structures.

12. Comparison of load spectra from literature and the VEAB chimney

Observations of the VEAB chimney have been in operation during six years. There is only one previously reported reference in the available literature with observations for a longer period of time (Pirner and Fischer 1999).

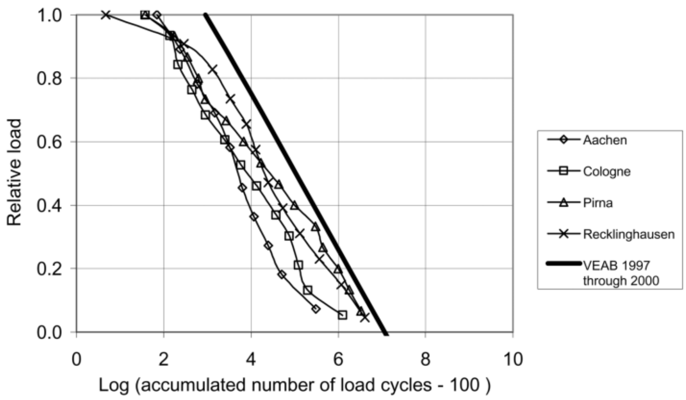


Fig. 19 Recorded amplitude spectra for the chimneys reported in Ruscheweyh, *et al*. (1998) and the VEAB chimney

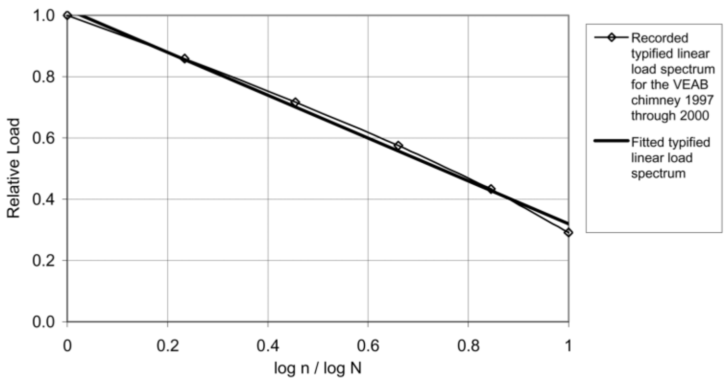


Fig. 20 Typified linear load spectrum for the VEAB chimney $\kappa = 0.32$

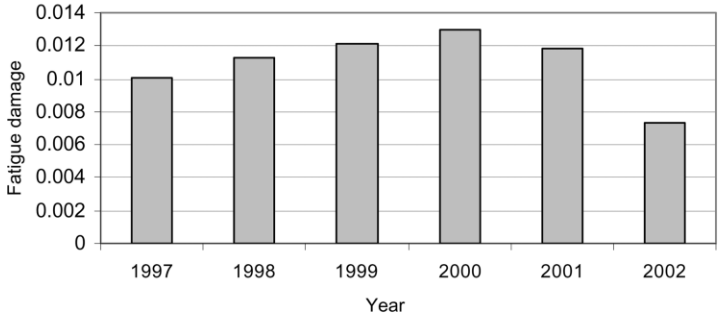


Fig. 21 Partial fatigue damage per year determined from recordings at 170 degree direction and for detail category $C = 30$. Accumulated fatigue damage for the six-year period is 0.0658

In Fig. 19 recorded spectra for Aachen, Cologne, Pirna, Recklinghausen (Ruscheweyh, *et al*. 1998) and the VEAB chimney are drawn.

In Fig. 20 a typified linear load spectrum as defined in BSK 99 (1999) was calculated with the least square method for the VEAB chimney is drawn.

13. Cumulative fatigue damage for period 1997 through 2002

It is found that the greatest fatigue damage during the recorded six-year period was 0.0658 for an estimated detail category $C = 30$. This means that $1 - 0.0658 = 0.9342$ or 93.4 percent of the fatigue life remains. If the recording period is assumed to be representative for the complete service life of 30 years the fatigue damage for the service life will be

$$0.0658 \cdot \frac{30\,\text{Years}}{6\,\text{Years}} = 0.33$$ which is less than 1.00 and thus satisfactory.

In Fig. 21 the partial damage fatigue (Palmgren-Miner summation) per year for the recording period and detail category $C = 30$ based on strain-gauge no 4 is shown.

14. Cumulative fatigue damage for vortex shedding period of large deflection ranges 2002-12-19 10.33 h through 11.12 h

Very large deflections were observed during a half-hour period on 2002-12-19, see Fig. 9. This behaviour of the chimney appears similar to what occurred in the winter 1995/1996.

Results from cumulative fatigue damage calculations for 2002-12-19 10.33 h to 11.12 h show a partial fatigue damage of 0.0016 for detail category $C = 30$. The calculations are made in accordance with Tranvik and Alpsten (2002). If the behaviour observed during the six-year recording period 1997 through 2002 is considered representative for the 30-year design life of the chimney, then the special lock-in behaviour observed in the 10.33-11.12 h period on 2002-12-19 may occur about 420 times before the fatigue life is fully used up, that is, the Palmgren-Miner summation will be equal to 1.

15. Discussion

Wind and structural data for a six-year period have been recorded for a very slender chimney (slenderness ratio $h/d = 39$). This data should have some general significance and may be useful in the evaluation of wind effects on slender structures, such as chimneys.

A period with very large oscillations of the chimney during the winter 1995/1996 was repeated in December 2002. Both occasions were in wintertime when there is a greater frequency of laminar wind flow, and the low temperature increases the air viscosity. At almost all periods with a wind velocity at or above the critical wind velocity for vortex shedding the chimney oscillates more or less perpendicular to the wind direction.

For mechanical pendulum tuned dampers at steel chimneys the following risks must be considered:

– Condensation in the damper house causing the friction mass to corrode or freeze and get stuck in the damper house.
– Wear could change the damper properties.
– Erroneous or careless handling during erection or service could make the damper inoperable by mistake.
– Design errors such as wrongly calculated natural frequencies may result in a mistuned damper with limited damping action.
– A mechanical pendulum tuned damper requires a program for regular maintenance. For the VEAB chimney it was decided to inspect the structure once a year.
– Snow and ice deposition on the chimney during the winter periods adds mass, which changes the natural frequency and the Reynold number, which may result in a completely mistuned damper, and may change the cross-sectional properties of the chimney as well. Also, the Reynold number may change if the chimney is charged with rainwater.

There is a need for revision of code models to estimate the response caused by vortex shedding of very slender structures (slenderness ratio $h/d \gtrsim 30$). The geometric properties of the VEAB chimney had been different from the actual geometric properties if one of the BSV 97, CICIND or ISO codes had been followed strictly. Vortex-shedding behaviour of very slender structures is not properly described by current structural models, which were derived from data for structures with limited deflections. For very slender structures it appears that large deformations will amplify the lock-in effects at vortex shedding.

16. Conclusions

Some major results of the investigation are as follows:

(1) A considerable amount of data has been collected for wind action and structural response of a very slender chimney during the six-year period 1997 through 2002.
(2) The behaviour of this chimney with a friction-type damper has been investigated, and a number of potential problems with such dampers identified, such as condensation in the damper house, wear, erroneous or careless handling during erection or service, and ice build-up causing added mass and changed Reynold number, which may result in a completely mistuned damper.
(3) For very slender structures the lock-in effects may be more pronounced than observed for structures with moderate slenderness.
(4) The recorded response spectra of the chimney correlate well with a typified linear spectrum.

(5) The results from the theoretical model developed for a two-mass spring and damper system are in agreement with observed behaviour of the chimney.
(6) Action of very slender steel chimneys at vortex shedding is not properly described by structural models in current codes.

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