FATIGUE DESIGNOF SMOKE STACKS

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Abstract

As vibrations from vortex-shedding occur at moderate wind speeds, structures undergo a considerable number of stress variations. So risk of fatigue is to be taken into account at the design stage itself. Even if a fatigue analysis is not demanded in the code to be applied, risk of fatigue is to be considered, especially with regard to slender steel chimneys due to larger volumes of material subjected to high stresses. Thus, risk of fatigue which has not been addressed in the Indian context, has been taken care in the present paper. It is envisaged that this formulation will be appropriate for inclusion in Indian codes and standards. As part of the case study, a chimney from an industry having Diesel Power Plant has been undertaken. Fatigue analysis of this chimney has been done and measures to reduce fatigue problem have been suggested.

Keywords: Vortex-shedding, Critical speed, Miner number, Scruton number, Logarithmic decrement

NOTATIONS

E : Modulus of elasticity, N/ mm^2

fn : Natural frequency of chimney, Hz

m : Power of fatigue curve

M : Miner number

n : Number of load cycles

n_1 : Number of cycles in life time

Nw : Equal cycles to collapse corresponding to Wohler stress

Nσ : Number of equal load cycles of stress σ

Re : Reynolds number

Sc : Scruton number

St : Strouhal number

Ucr:: Critical wind speed, m/sec

ymax : Maximum deflection amplitude, m

σ : Stress, N/ mm^2

σi : Measured real amplitude of stress, N/mm^2

σ_{max} : Maximum stress (happens only once), N/mm^2

σw : Wohler stress, N/mm^2

Δσw : Double amplitude of the vibrating stress at test, N/mm^2

ΔσA : Double reference stress for (NA = 2×106), N/mm^2

λ : Correlation

ρ : Density of air/steel, kg/m^3

δ : Logarithmic decrement for the material of chimney

vair : Kinematic viscosity of air = 1.46×10-5 m^2/s at 15^{o}C and standard atmospheric pressure

VIV : Vortex-Induced Vibration.

I.INTRODUCTION

Stacks of height up to 120 m are made of steel as it is the most economic design. But, steel stacks have lower structural damping and lower masses in comparison with concrete stacks and therefore wind-induced vibrations caused by vortex-shedding are important for structural design. 'Vortex- shedding' is loading at the resonance frequency and causes fluctuating stresses [1, 2]. If stack vibrates at a frequency of 1 Hz; its material is loaded and unloaded 3600 times in an hour, so one full day of vibration would cause the stack to be loaded and unloaded 86000 times. If the fatigue life of such a structure is as high as one million loadings, it might reach this stage in a total period of only 14 days [3, 4]. The growing importance of the problem is coupled with lack of simple calculation criteria. Number of stress cycles at different stress levels is to be considered. The problems arising from vortex-shedding are assessed by consideration of a non-dimensional mass damping parameter 'Scruton number' [1, 2].

- If Sc> 15, crosswind oscillations will be so small; no action against vortex-shedding is required.
- If Sc< 5, crosswind oscillations will be violet and vortex suppression/damping devices are mandatory.
- If 5 <Sc< 15, check for fatigue cracks is required and designer is permitted to use the stack; if response calculations confirm that it will not suffer from fatigue damage.

II. RELATION BETWEEN FLUCTUATING STRESS AND NUMBER OF LOAD CYCLES

Most of the fatigue tests on steel are performed by loading the material with a constant stress amplitude and temperature. Number of load cycles Nσ up to formation of crack is determined and is given as the result of test. The real stress fluctuations in wind, however, vary. The stress, calculated as maximum value will occur rarely. The real fluctuating stresses as found by measurements for four different steel stacks in Germany as a function of number of cycles are shown in Fig.1. The measurements have been made continuously up to 2 years. Table1 shows main dimensions and characteristic values of steel stacks.

III. EFFECT OF FATIGUE

Fatigue is the damaging effect of all stress fluctuations together. Contribution of one load cycle to fatigue with amplitude σ is 1/Nσ, where Nσ is number of equal load cycles of stress σ. The contribution of n load cycles of level σ, thus n(σ) cycles, is n(σ)/Nσ.. The reduction of resistance or the addition to fatigue of many load cycles at varying amplitudes is expressed by summing up all the values n(σ)/Nσ of all load cycles. The number is called 'Miner number' [5, 6]. If Miner number is close to 1 then cracks are expected. Miner number is calculated by arranging stresses in reducing order. The relation between stress σ, caused by load, and number of cycles, as found in tests is shown in Fig.2.and is written as mentioned in table 1.

$$\sigma = \sigma_{max}\left(1 - \frac{log_{10}\, n}{log_{10}\, n_1}\right)^{\lambda} \qquad [1]$$

Where, λ = 1 if U_{cr}> 8 m/s

If U_{cr}< 8 m/s, then $\lambda = \left(\frac{U_{cr}}{8}\right)$

If λ = 1 then relation between σ and n is linear on a logarithmic scale.

The ratio of stresses σ due to loading and stress σw, where w stands for Wohler, is to be integrated over N to find Miner sum [7, 8 and 9].

The relation between Nw and stress level is shown in Fig.2. The relation is:

$$\sigma = \sigma_w \left(\frac{N}{N_w}\right)^{\lambda} \qquad [2]$$

Drawn on double logarithmic paper the relation below yield stress is a straight line. The relation between number of load cycles, N, causing cracks and double stress amplitude, Δσ is:

$$\Delta\sigma_w = \Delta\sigma_A \left(\frac{N_A}{N}\right)^{1/m} \qquad [3]$$

m = 3 for N < 5×10^6, m = 5 for N > 5×10^6 and m = ∞ for N > 10^8.\

From test results as shown in Fig.2, it is concluded that the stress with double amplitude ΔσA causes fatigue cracks after 2×106 fluctuations (NA = 2×106). Fatigue will not occur if double stress amplitude remains below 26 N/mm2 [10 and 11].

IV. MEASURES TO REDUCE FATIGUE

If stack is subjected to repeated resonant vibrations, its design and fabrication is to be checked to ensure that stress concentrations are reduced as far as possible. Double stiffeners should be provided to support the flanges as shown in Fig.3. Bolts, especially high tension bolts, are particularly vulnerable to fatigue because they are preloaded in tension and thread is a large stress raiser. Often the fracture or stretching of bolts, or the stripping or loosening of nuts, is the first visible sign that there is a fatigue problem caused by vibration. Any occurrence of a failure of several bolts in a chimney should prompt an investigation of vibration [3, 12]. Vortex suppression devices such as shrouds, helical strakes, spoiling plates and vertical vanes or damping devices should be fitted to stack to minimize the VIVs and to increase fatigue life [5, 13, 14].

Table1. Main Dimensions and Characteristic Values of Stacks, Germany [2]

Identification-Location			Chimney1 Aachen	Chimney2 Koln	Chimney3 Pirna	Chimney3 Pirna*	Chimney4 Reckling
Height	H	m	28	35	60	60	38
Diameter	D	m	0.914	0.813	2	2	1.016
Slenderness ratio	H/D	-	31	43	30	30	37
Natural frequency	f_n	Hz	1.72	0.612	0.802	0.77	0.68
Logarithmic decrement	δ	-	0.015	0.015	0.015	0.125*	0.03
Scruton number	Sc	-	2.56	7.33	1.90	17.23	10.71
Critical wind speed	U_c	m/s	7.9	2.5	8.0	7.7	3.5
Reynolds number	Re	-	4.8E+05	1.3E+05	1.1E+06	1.0E+06	2.3E+05
Measured/ observed	y_{max}/D	-	0.38	0.48	0.25	0.03	0.07
Measured/ observed	y_{max}	mm	347 (M)	388 (M)	500 (M)	60 (M)	74 (M)
Observation period			2 years	2years		2 years	2 years

* This chimney fitted with damping device, M – Measured

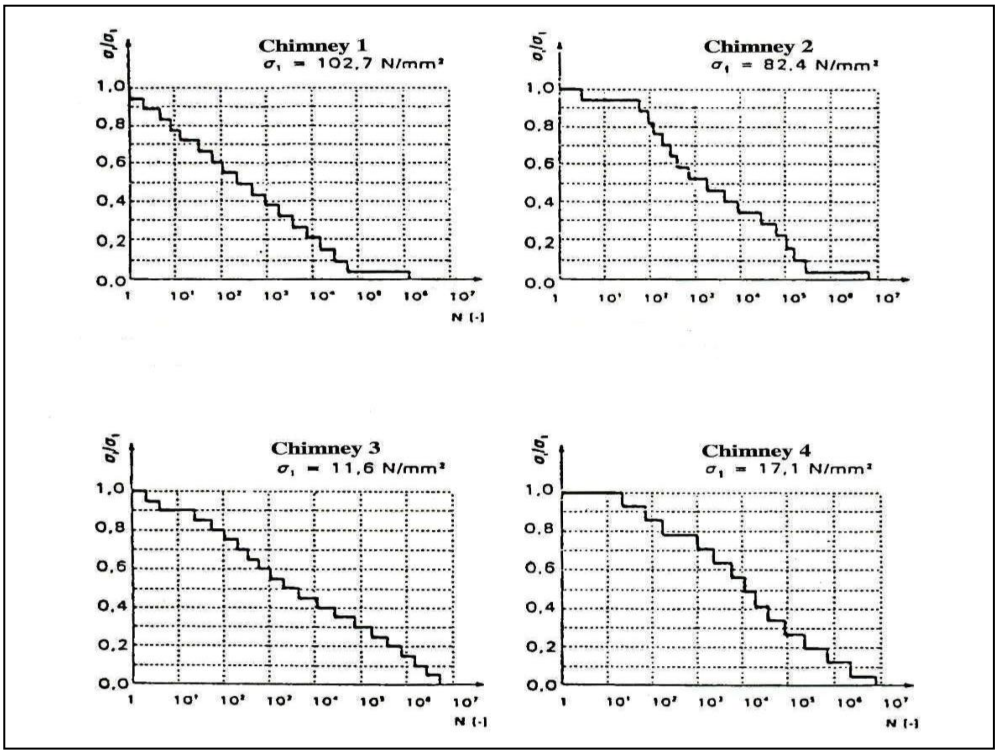

Fig.1. Measured amplitude v/s Load Cycles for Four Chimneys, Germany [5]

σ_1 : Maximum stress of measured data of each collective, N/mm^2

σ_i : Measured real amplitude of stress, N/mm^2(Fig.1.)

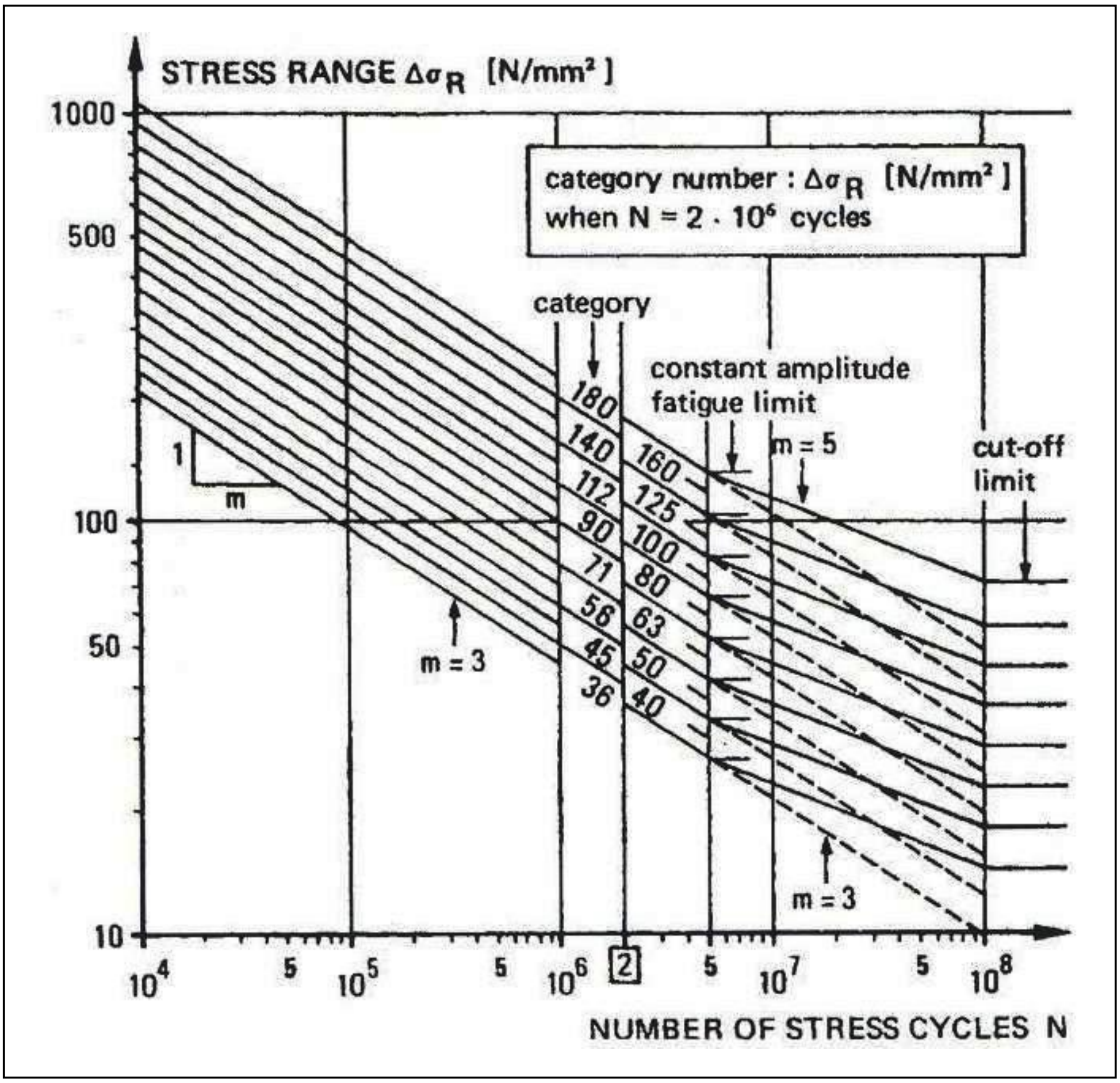

Fig.2. Fatigue Strength of Base Material at Different Detail Categories [2, 10]

Fig.3. Modified Flange with Double Stiffeners

Case Study of Fatigue Analysis of Chimney from an Industry

Data of case study chimney taken from site and from calculations are [16]:

Height of stack, H = 56 m, Dia. at top of stack, D = 1.5 m, Dia. at base, Dc = 2.4 m, St = 0.2, fn = 0.73 Hz, Uc= 5.5 m/s

Scruton number is found by: $$Sc = \frac{2m\delta}{\rho_{air}D^2}$$

Where, m = mass per unit length of top third, kg/m

δ = 0.05 for unlined steel chimneys [Ref.15]

ρair = 1.25 kg/m3

D = mean overall diameter of top third of chimney, m

$$m = \frac{1.05(1183.8 + 2367.5 + 2959.4)}{20} = 341.8\ kg/m$$

$$Sc = \frac{2 \times 341.8 \times 0.05}{1.25 \times (1.5)^2} = 12.15$$

As 5 <Sc< 15; calculations are required for fatigue damage.

Reynolds number is calculated from critical wind speed.

$$Re = \frac{DU_c}{\nu_{air}}$$

$$Re = \frac{1.5 \times 5.5}{1.5 \times 10^{-5}} = 5.5 \times 10^5$$

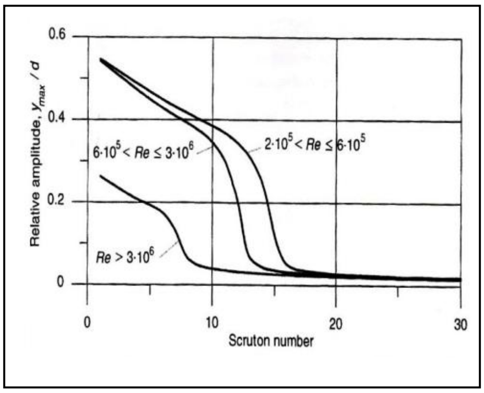

Fig.4. shows variation of relative amplitude as a function of Sc according to CICIND Model Code [2].

From Fig.4

$$\frac{y_{max}}{D} = 0.32$$

ymax = 0.32 × 1.5 = 0.48 m

Mbase = 2545.862 kN-m [Ref. 16]

$$\sigma_{max} = \frac{M_{base} \times D_c}{I \times 2}$$

$$\sigma_{max} = \frac{2545.862 \times 10^3 \times 2.4}{0.08514 \times 2 \times 10^6} = 35.88\ N/mm^2$$

ΔσA = 35.88 × 2 = 71.76 N/mm2

The expected number of cycles, N, during a period of T years:

$$N = 3.15 \times 10^7 T f_n P$$

T = Lifetime of stack=50 years (assumed)

P = Probability that the mean wind speed is in a range 1.3 Uc and U = 0.284 [Fatigue life calculations are from Euro-code, Dyrbye, 1999]

$$N = 3.15 \times 10^7 \times 50 \times 0.73 \times 0.284 = 3.32 \times 10^8\ cycles$$

As N calculated above is greater than 2×106 fluctuations. Permissible Δσ = 26 N/mm^2 and Δσ causes fatigue cracks after 2×106 fluctuations. As the double stress amplitude is greater than 26 N/mm^2, 'Triple Helical Strakes' were fitted at the top 1/3rd portion of chimney.

Otherwise, a 'Tuned Mass Damper' may be installed at the top of chimney. It will increase the damping leading to a logarithmic decrement of 0.1 to 0.2. This will decrease Δσ below 26 N/mm^2, making it safe for fatigue design.

V. CONCLUSIONS

- Fatigue failure starts in parts that are in tension. Mostly, bolted flange connections, welded stiffeners at the bottom and anchor bolts at the base are more vulnerable to fatigue.

- If Miner Number, M is greater than 1; cracks are expected.
- ΔσA causes fatigue cracks after 2×106 fluctuations as shown in Fig.2. Fatigue will not occur if ΔσA remains below 26 N/mm^2. If ΔσA is above 26 N/mm^2, then logarithmic decrement of the steel chimney is to be increased in steps by installing vortex suppression devices. As damping is increased, Scruton number also increases.
- These calculations are based on tests at ambient temperature. At elevated temperatures, stresses causing fatigue cracks will be reduced. Measures as suggested above should be taken at the design and manufacturing stage itself to avoid the fatigue failure problem.

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