THE ANALYSIS OF A WIND INDUCED FATIGUE FRACTURE IN ENERGY PLANT EQUIPMENT

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The paper describes the rupture of a 4m long horizontal tube of commercially pure aluminium 1050 A in the H18 condition, supported in its extremities on two 7m height vertical columns. The tube is an electrical conductor of 7.5mm thickness and 100mm external diameter, plastically deformed in its extremities to produce flatenned ends which are fastened by screws to the columns. The rupture in service of this electrical conductor ocurred in one of the extremities, in the transition between the plastically deformed flatenned part and the normal tubular geometry.

INTRODUCTION

The rupture of a 4m long horizontal tube of commercially pure aluminium 1050 A in the H18 condition, supported in its extremities on two 7m height vertical columns, is presented and discussed. This structure is part of an electricity generation facility, and is placed in open air. The tube is an electrical conductor of 7.5mm thickness and 100mm external diameter, plastically deformed in its extremities to produce flatenned ends which are fastened by screws to the mentioned columns. The rupture in service of this electrical conductor occurred in one of the extremities, in the transition between the plastically deformed flatenned part and the normal tubular geometry. The study identifies the rupture as a wind induced fatigue failure in an high stress concentration region, which is also subjected to an important plastic deformation during the fabrication. The mechanical properties of the material, including fatigue SN curves obtained under rotating bending conditions, were determined, and the possible influence of the temperature at which the plastic deformation (flatenning) of the extremities is carried out was assessed.

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A model of the component life under wind loading conditions was then produced, taking into account the stress state resulting from the random statistically characterised wind loading. Design recommendations in order to avoid future similar problems are described.

The paper presents a failure analysis case study, where a methodology to deal with wind loading is proposed and provides the basis for understanding the failure.

MECHANICAL TESTING

Tensile tests were performed on material taken from the plastically deformed regions (flatenned ends) and of the non-deformed cylindrical region. Results for the three forming temperatures examined are presented in Table 1.

TABLE 1 Tensile testing on deformed and non deformed material

	plastically deformed			cylindrical region (non-def.)		
temp.	tensile strength	yield stress	elong.	tensile strength	yield stress	elong.
°C	Nmm^{-2}	Nmm^{-2}	%	Nmm^{-2}	Nmm^{-2}	%
200	107	99	12	113	109	10
250	96	85	17	112	105	12
300	90	75.5	11	121	103	12

Hardness measurements were performed in deformed and non-deformed material, heated at 200, 250 or 300°C; results were essentialy independent of the region where the measurement was taken, and were 38, 39 and 37HV5 respectively. Rotating bending fatigue tests were conducted on material taken from the flatenned part of tubes heated at the three temperatures mentioned. The SN curves are presented in Figure 1. The statistical analysis of the data points showed that the fatigue behaviour for the three material conditions examined, although very similar, can be expessed by three independent straight lines of equal slope. The fatigue strength for material deformed at 200°C is slightly better than for material deformed at 250 or 300°C. A first point of the analysis is that the increase in the forming temperature reduces both the static and fatigue strength properties, as shown in Table 1 and Figure 1 respectively. However, a compromise must be established regarding the forming temperature, since its increase favours the plastic deformation process during the manufacture of the part.

SERVICE BEHAVIOUR

Since this is an open air structure, it is subjected to wind loading, besides its own weight. As mentioned by Boulton and Chadwick (1), the behaviour of such a structure is a function of several factors, such as its damping properties, the degrees of freedom where it may vibrate, the natural frequency, its aerodynamic properties and the characteristics of the wind loading. In particular, the wind may induce vibration perpendicular to its flow, due to the von Karman vortices, Figure 2. This phenomenon may be critical if the frequency of vibration is similar to the natural frequency of the tube.

The analysis performed assumes that the tube vibrates as described in Figure 3. It is supposed to be built in its extremities, since the vertical columns are supposed to be very much stiffer than the horizontal tube. The tube is flexible and has low damping, given its geometry and the low modulus of the material; thus, it is assumed that the tube responds directly with the forcing function, taken to be the wind velocity, (1). Since the wind speed follows a Rayleigh distribution, (2), the hypothesis was made that the stress due to the wind loading could be described by a Rayleigh probability density function:

$$p(S) = \frac{S}{\sigma_{rms}^{2}} \exp\left(\frac{-S^{2}}{2\,\sigma_{rms}^{2}}\right) \qquad (1)$$

where σ_{rms} is the root mean square of the process and S is the peak stress. This function is sketched in Figure 4. Based on ref.(1), it was assumed that σ_{rms} is equal to the yield stress divided by 4, and that the maximum stress in the critical region is the material's yield stress. Thus, for the 200°C material condition, σ_{rms} is equal to 25Nmm^{-2}. The natural frequency of the tube was calculated to be 17.6 Hz. The vortices formation frequency was calculated using the expression, ref.(3)

$$f_v = S_t \; v/D \qquad (2)$$

where S_t is Strouhal's number (0.2 for cylinders), v is fluid speed and D diameter. Critical wind speed is therefore 8.8m/s. Another approximate analysis, based upon ref. (4), gave 6.2m/s.

It is assumed that the maximum stress in the critical region (transition between flat extremity and tubular region) is the material's yield stress, and that the stress distribution follows a Rayleigh distribution. Miner's fatigue damage rule was used, in the form, ref.(5)

$$D = \int_0^\infty \frac{n_0\, p(S)}{N(S)}\, dS \qquad (3)$$

where n_0 is the total life, p(S) is the probability density function and N(S) is the SN curve of the material. For this material condition the SN equation is (Figure 1)

$$N(S) = 2.3 \cdot 10^{17}\, S^{-6.6578} \quad (S,\ \mathrm{Nmm}^{-2}) \qquad (4)$$

Using as upper limit for the integral 99Nmm^{-2}, n_0 is 2.10^{6} and D = 0.72 if the mean SN curve is used; n_0 = 10^{6} and D = 0.65 if the lower SN curve for 98% confidence level is used.

Statistically, for the area of interest wind speed is higher than 6m/s 1.2% of time. Thus, assuming that the tube vibrates always at 17.6Hz, 6.6·10^{6} cycles/year will be the expected number of cycles, showing that the tube has no adequate fatigue resistance. Even taking into account the conservative assumptions made, namely that the wind will always flow perpendicular to the tube, it is clear that the fatigue strength is inadequate, which justifies the premature failure that occurred in service.

CONCLUSIONS

The tubular electric conductor studied may suffer fatigue rupture due to vibrations induced by wind flowing perpendicular to the tube's axis. In order to improve the fatigue strength, a new design of the connection between the horizontal tube and vertical columns is required, which should reduce the stress concentration and the amount of plastic deformation necessary to manufacture the extremity.

REFERENCES

(1) Boulton, C.F. and Chadwick, D.B., "A Theoretical Fatigue Analysis of a Slender Mast Structure Subject to Wind Loading", The Welding Institute, Report 35/1977, 1977.

(2) Commission of the European Communities, "Wind Energy. Solar Energy R&D in the European Community", Series G, Vol.2, Reidel Publishing Co., 1986.

(3) Gurney, T.R.,"Fatigue of Welded Structures", Cambridge University Press, 1978.

(4) Almar-Naess, A., "Fatigue Handbook. Offshore Steel Structures", Tapir Publishers, 1985.

(5) Clough, R.W. and Penzien, J.,"Dynamics of Structures", McGraw-Hill, 1975.

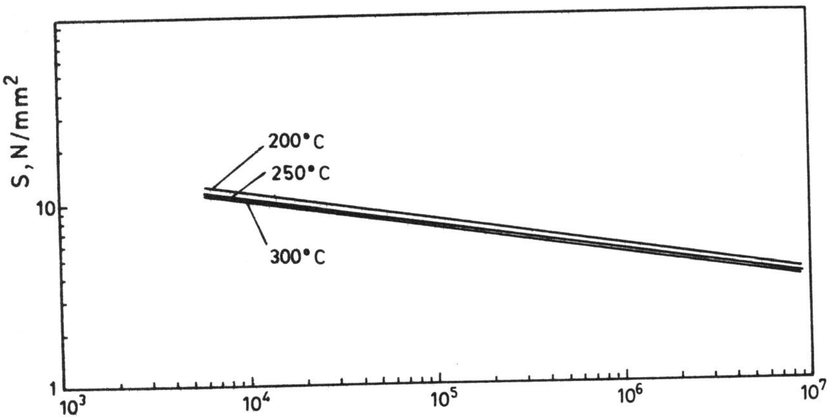

Figure 1 - SN curves for commercially pure 1050 A in the H18 condition, conformed at 3 temperatures

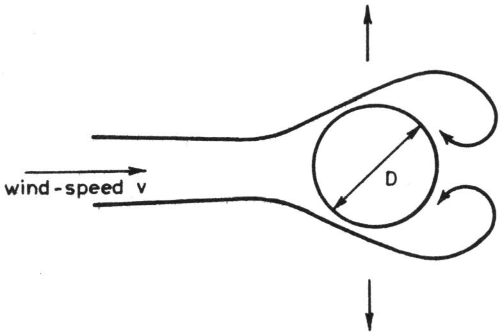

Figure 2 - Schematic representation of von Karman vortices

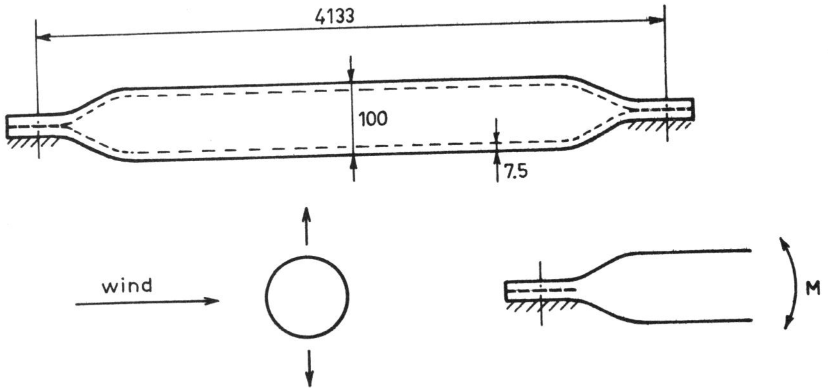

Figure 3 - Vibration of the electrical conductor

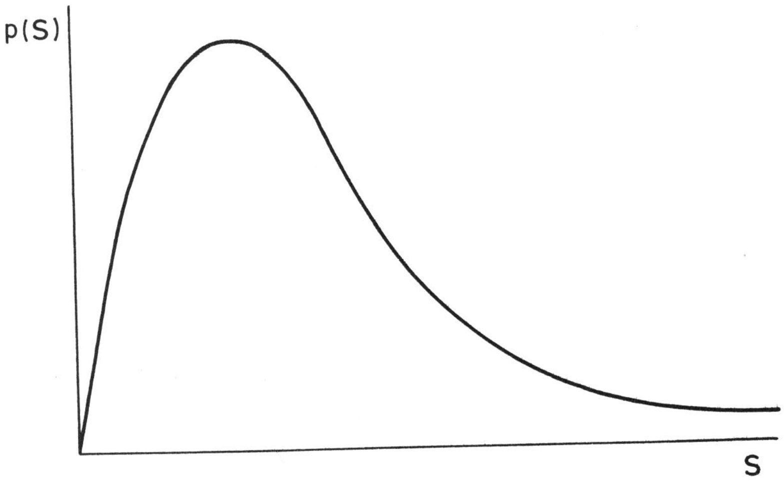

Figure 4 - Schematic representation of the Rayleigh distribution