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Wind-induced fatigue loading of tubular steel lighting columns

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Abstract. Two 12 m high tubular steel lighting columns have been instrumented to determine the wind-induced fatigue loading experienced by such columns. Each column supported a single luminaire mounted on a 0.5 m long bracket. One column was planted in soil, and the other bolted through a welded baseplate to a substantial concrete base. The columns were strain gauged just above the shoulder weld which connected the main shaft to the larger base tube. Forced vibration tests were undertaken to determine the natural frequencies and damping of the columns. Extensive recordings were made of response to winds with speeds from 4 m/s to 17 m/s. Selected records were analysed to obtain stress cycle counts and fatigue lives. Mean drag coefficients were also derived from the strain data to investigate experimentally the effect of Reynolds Number.

Key words: wind loading; fatigue; drag; lighting columns; street lights; lamp-posts.

1. Introduction

A European Standard, prEN 40, is being drafted by CEN/TC 50 for the design and verification of lighting columns (CEN 1997). This draft incorporates fatigue criteria developed for the Highways Agency by Flint & Neill Partnership which is contained in the Highways Agency design document BD 26/94 (Highways Agency *et al.* 1994). Fatigue is receiving particular attention because of the occurrence in recent years of premature fatigue damage to tubular steel lighting columns ('lamp-posts' or 'street lights') located on exposed sites. This has prompted investigations to derive more reliable design procedures to safeguard against wind-induced fatigue failure.

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Results are presented from a recent test programme which monitored two representative, 12 m high, tubular steel lighting columns that were identical apart from their foundation detail: one was ‘planted’ (erected in a 1.7 m deep back-filled hole), the other was bolted through a welded flange plate to a substantial concrete base. Different base fixity details were studied because these may influence the wind-induced response of the columns, and hence also the fatigue loading.

2. Experimental details

2.1. Lighting columns

The 12 m high tubular steel columns (Fig. 1) were of 140 mm diameter and 3 mm wall thickness, and each was welded to a larger base tube of 194 mm diameter and 4.5 mm thickness at a position approximately 1.5 m above ground level. Each column supported a single 7.8 kg luminaire at a

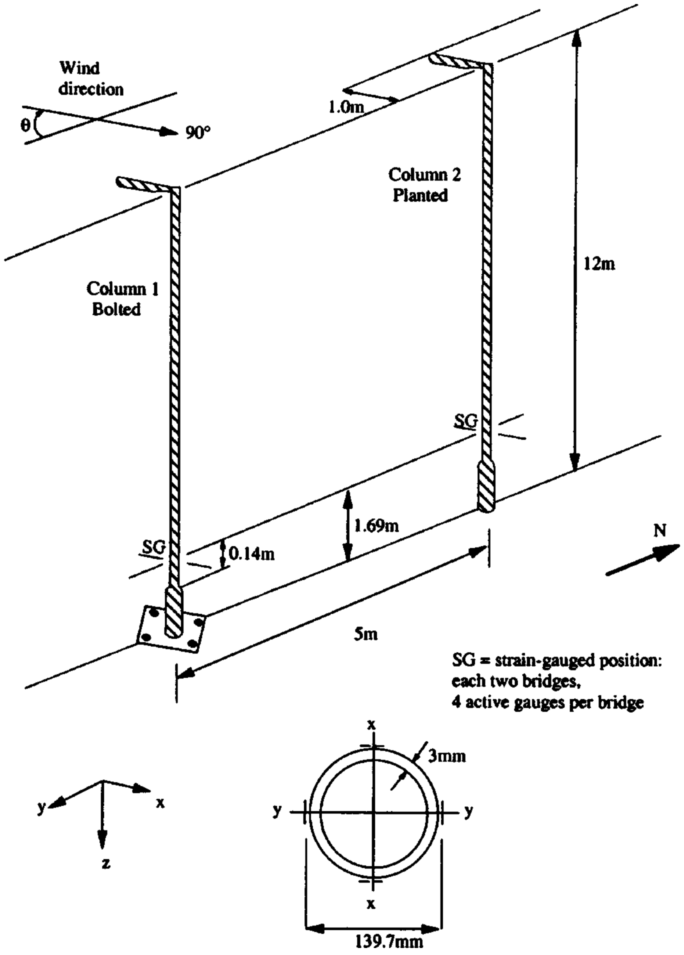

Fig. 1 Schematic of instrumented lighting columns

lateral out-stand of 0.8 m to the centre of the luminaire. The two columns were erected on the wind engineering site at Silsoe Research Institute.

2.2. Instrumentation

Each column was instrumented identically with strain gauges just above the base section weld (Fig. 1), and with three-component accelerometers and a laser located within the luminaire. Strain gauges were bonded to the outside of the main shaft at a position of one diameter (140 mm) above the weld at the top of the tapered shoulder connection between the base and main shaft. Eight gauges were bonded in four pairs on two orthogonal axes. Diametrically opposite pairs were wired to provide a full bending bridge (four active gauges per bridge) on each of the two orthogonal axes. One bridge of four gauges was bonded in the plane of the luminaire and was referred to as the x-axis plane, the orthogonal plane being referred to as the y-axis plane. Each bridge output was amplified and calibrated to give a maximum differential strain reading of 1213 $\mu\varepsilon$ with a resolution of 0.6 $\mu\varepsilon$ when connected to the 5 V A-to-D card in the PC data-logger. Care was taken to ensure that no gauges were placed near to the seam weld of the tube. With the bolted-base column, this necessitated rotation of the luminaire bracket by 45°, resulting in the luminaire being atypically orientated along a diagonal of the four base bolts instead of parallel to a pair (Fig. 1). A 3-axis accelerometer assembly and laser were installed within each luminaire (approximately in the position normally occupied by the filament) but results from these are not discussed in this paper.

2.3. Reference anemometry

A Gill ultrasonic anemometer mounted at 10 m height was used to monitor the approach wind speed and direction. The sonic anemometer recorded the three components of air speed, from which the horizontal wind speed and direction can be computed. The 4 Hz output from the sonic anemometer was recorded on the same PC as was used to record the column strains and accelerations.

3. Data collection

Recordings of wind-induced response and associated wind conditions started on 8 December 1997 and ended on 14 March 1998. During this period, some 472 data records were collected embracing wind speeds of 4–17 m/s and wind directions of 32°~339°. Each record was of 30 mins duration, with the 4 strain channels and 6 acceleration channels being recorded at a 12 Hz sampling rate (sampling at 20 Hz, 40 Hz, and on a few occasions at 585 Hz was used in some runs to obtain more detailed information for spectral analysis) and the sonic anemometer at a 4 Hz sampling rate. For these 236 hours of measurements, the instrumentation was controlled automatically to record only when prescribed wind conditions (in relation to both a threshold speed and a band of directions) arose. Additionally, continuous time-averaged records were kept which enabled strain ‘zeros’ under calm conditions to be monitored. Periodically, qualitative monitoring of wind-induced response was undertaken using the laser mounted within each luminaire.

Under particularly calm conditions, two additional response measurements were made. The first was of strains under controlled horizontal static loading of up to 2 kN applied at 5 m above ground level. The second was of the dynamic response following a step function load input (achieved by cutting a tensioned chord attached to the column 4–5 m above the ground), and following forced vibration at the natural frequency (achieved manually again using a chord attached to the column 4−5 m above the ground). The static loading provided a check on the functioning of the strain gauges, and the dynamic decay measurements enabled the natural frequency and damping of the columns to be determined.

4. Experimental results

4.1. Static loading

The static loading tests gave strain readings that were reasonably close to, but on average 8−9% less than, the expected theoretical values, implying that the wall thickness of the shaft tubes was some 8−9% greater than the nominal 3 mm value. Subsequent measurements of steel and galvanising thicknesses were not conclusive, because of variations in readings caused by the difficulty in registering consistently the flat probe head against the curved external surface of the shaft tube, and because of spatial variations in galvanising thickness.

4.2. Natural frequency and damping

The response decay following the forced vibration and step-load input excitations were plotted as a function of time. A mathematical model was then applied to simulate the decay measurements. Parameters within the model were natural frequency, damping (in the form of a logarithmic decrement), and ‘cross-talk’. One observation was that as forced oscillations decayed, they were progressively transferred to oscillations in the orthogonal plane, and then back to the original plane again, and so on. This ‘cross-talk’ occurred at a beat frequency of approximately 0.028 Hz (35 s periodicity) and arose either because of a torsional mode of vibration produced by the eccentricity of the luminaire at the top of the column, or because of a marginally different first-mode frequency of vibrations in the two orthogonal planes which arises because of the access hole cut in the base tube. It was found from the model that, for the planted column, the damping varied according to the amplitude of oscillations, being greater for larger amplitude oscillations. This finding is consistent with those of Pagnini and Solari (1999) from work on steel poles and monotubular towers. They considered damping to arise from the three sources of aerodynamic damping, mechanical damping (structure/foundation/soil interaction) and structural damping (energy dissipated in the material and connections). They argued that structural damping dominated with their columns, particularly for fundamental mode oscillations, and that this damping increased parabolically with amplitude of oscillations. In the present tests it was considered that damping due to energy dissipation in the soil became increasingly significant with the planted column as the amplitude of oscillations increased. At larger amplitudes, relative movement between the column and the ground was observable, as were gaps and cracks in the soil around the column. The model was therefore further developed to include damping as a function of amplitude (i.e., time). By fitting the model to the measurements, the natural frequency, damping, and beat frequency could be identified reliably and conveniently. The mathematical model is given by:

$$A = \cos(f_n t) e^{(-f_n t \delta / 2\pi)} A_0 [1 - B \sin^2(f_b t/2)] \tag{1}$$

$$\delta = D e^{(-tE)^2} \tag{2}$$

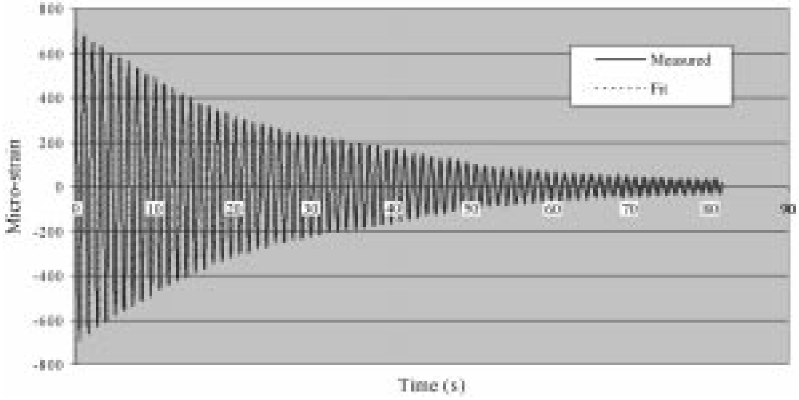

Fig. 2 Decay of forced vibration of bolted column

where A = amplitude of oscillation (in $\mu\varepsilon$ from mean value); A_0 = initial amplitude of oscillation (in $\mu\varepsilon$ from mean value); B = cross-talk constant ($0 \leq B \leq 1$); D = log dec damping at amplitude A_0; E = reduction constant for damping; f_b = beat frequency of cross-talk; f_n = natural frequency (1st mode); t = time; and δ = log dec damping.

Fig. 2 shows the decay of forced vibrations in the x-plane for the bolted column. In this case, the column was manually excited at 45° to the x-plane, i.e., about a plane parallel to the pairs of base bolts, which appeared to be a preferred plane of vibration. Also shown is the mathematical fit obtained from Eqs. (1) and (2) with $A_0 = 710\,\mu\varepsilon$, $B = 0.02$, $D = 0.044$, and $E = 0$ (i.e., no amplitude dependency), which is nearly indistinguishable from the measured response. Thus, for the bolted column, the log dec damping, δ, is given as 0.044, the natural frequency, f_n, as 5.6 rad/s, or 0.89 Hz (1.12 s), and the beat frequency, f_b, as 0.17 rad/s, or 0.028 Hz (36 s). The beat frequency of the bolted-base column is not particularly apparent in the response, because it was excited about a plane of a pair of base bolts which appeared to be a preferred plane of vibration.

Fig. 3 shows the equivalent plot for the planted column, but in this case the column was manually excited in the x-plane. Here, the beat frequency is apparent. Fig. 4 shows the corresponding

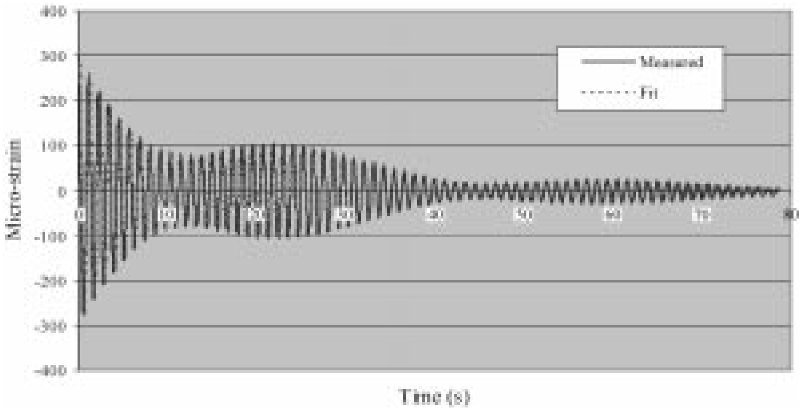

Fig. 3 Decay of forced vibration in x-plane of planted column

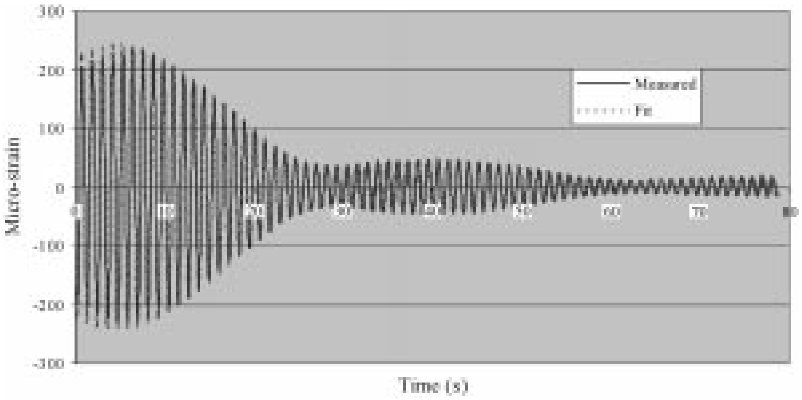

Fig. 4 Cross-talk vibration in y-plane of planted column

response in the orthogonal y-plane, which clearly illustrates the cross-talk. The mathematical fit is also shown in each figure, and again the agreement is very good. For the planted column, the mathematical parameter values used were $A_0 = 563\ \mu\varepsilon$, $B = 0.6$, $D = 0.067$, and $E = 0.002$, giving the initial log dec damping, δ, as 0.067, the natural frequency, f_n, as 5.51 rad/s, or 0.88 Hz (1.14 s), and the beat frequency, f_b, as 0.18 rad/s, or 0.029 Hz (35 s). The initial δ value corresponds to oscillations producing strains at the strain gauged position of some 560 $\mu\varepsilon$.

For the 12 m high test columns, an approximate relationship between the amplitude of oscillation, a, (at the head of the column) and strain at the strain-gauged position is given by :

$$a = 0.79\varepsilon \tag{3}$$

where ε is in $\mu\varepsilon$ and a is in mm. Thus the initial δ value for the planted column corresponds to oscillations with an amplitude of some 440 mm. The damping decreases as the amplitude of oscillations decrease, as indicated by Eq. (2).

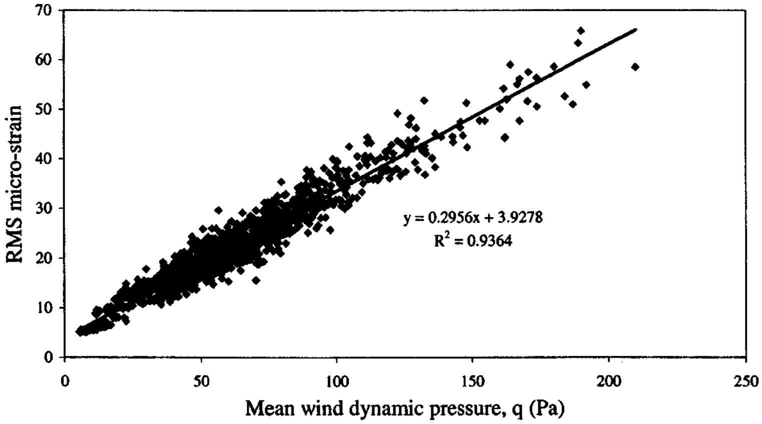

Fig. 5 Regression plot of RMS micro-strain and mean wind dynamic pressure for planted column

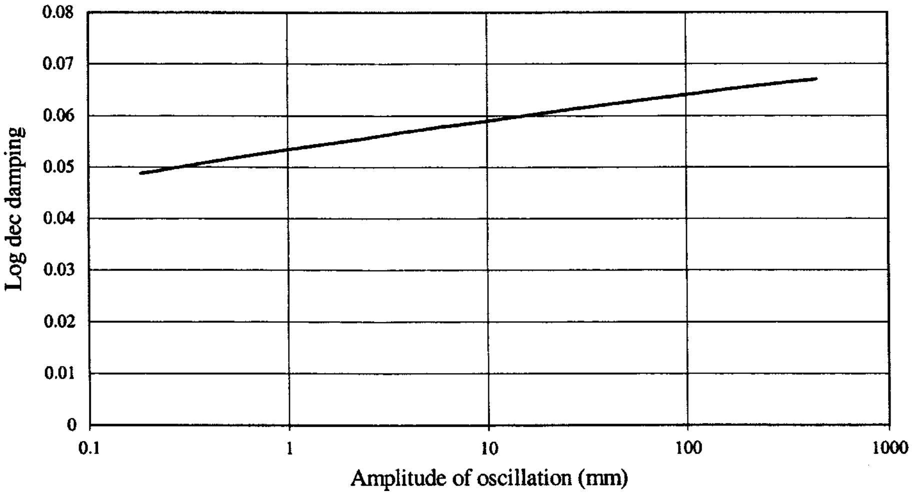

Fig. 6 Variation of damping with amplitude of oscillation for planted column

Where the damping is a function of the magnitude of oscillations (i.e., the planted column), it is potentially more useful to express this dependence as a function of wind speed instead. This requires a relationship to be found between wind speed and magnitude of wind-induced oscillations of the lighting columns. Fig. 5 shows a plot of root-mean-square (RMS) of measured micro-strain against mean wind dynamic pressure, q, (in Pa) for the planted column, for some 1300 records of 10 mins duration embracing a wide range of wind speeds.

Thus, an approximate empirical expression can be found between $\varepsilon_{\mathrm{rms}}$ and mean wind speed, V, (in m/s), and so, from Eq. (3), between V and a (in mm):

$$V = 2.6\sqrt{a} \tag{4}$$

which relates a mean wind speed and an RMS response.

Fig. 6 shows the variation in damping, δ, with amplitude of oscillation, a. This may be translated to a function of mean wind speed, V, by means of Eq. (4). It can be seen that a δ value of around 0.05 or 0.06 (i.e., a little higher than the value for the bolted base case) would appear to be reasonable for design application. The natural frequencies of the two columns were almost identical. The natural frequency, f_n, was also identified, independently, from spectra of wind response (see following section).

4.3. Wind-induced response and fatigue loading

Most of the strain data records were sampled at 12 Hz. However, some records were sampled at higher frequencies to obtain more revealing power spectra information. Fig. 7 shows a power spectrum of the x and y strain response for the planted lighting column when the response was sampled at 585 Hz and the data unfiltered. The data record was of 112 s duration and for a near westerly wind (approaching at 15° from the plane of the luminaire) with a mean speed of 7 m/s. This clearly shows the dominant first flexural mode of vibration at just under 0.9 Hz, and a second pronounced peak at approximately 5.6 Hz. The second peak is indicated from a finite element

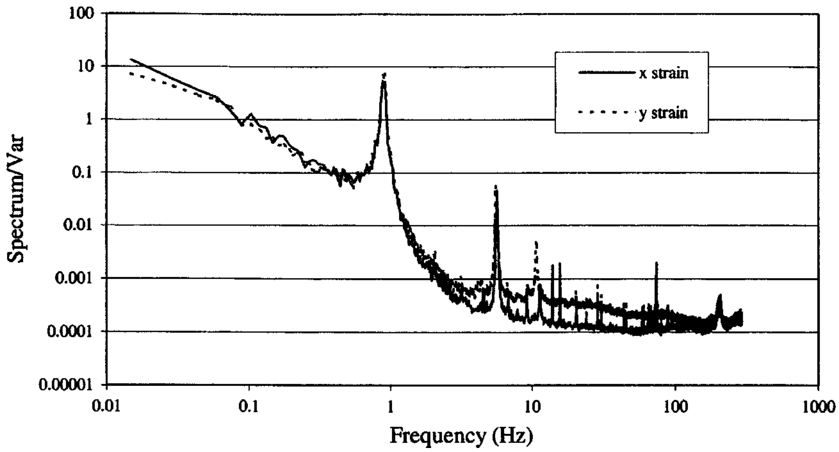

Fig. 7 Power spectrum of x and y strains for planted column (585 Hz data, 7 m/s wind)

modal analysis to be the next highest flexural mode of the column. The spectra show there to be little signal content above the 12 Hz sampling rate at which the majority of the records were collected, although there is evidence of further, less significant peaks at around 11 Hz, which are indicated from the structural modal analysis to be the torsional mode which arises because of the access hole cut in base tube and the eccentric luminaire mass at the top of the column. Circumstantial evidence supports the notion of higher mode responses insofar as, under moderate winds, the columns can be observed to flutter in a ‘belly-dancing’ manner.

To obtain the required fatigue loading data from the strain records, it was decided after consideration to process the raw data from one of the two strain channels on each column (that on the x-plane was chosen). The resultant of the two orthogonal strains was considered as an alternative, but the omni-directional behaviour of the columns and the availability of records for a wide range of wind directions favoured the analysis of a single channel since this was a direct measure of the fatigue loading at a point on the circumference of the weld, and was representative of the fatigue loading at any other point.

To convert the variable amplitude strain records into fatigue loading data it is necessary to undertake cycle counting (e.g., by the Rainflow or Range Pairs Method). For this project, this analysis was undertaken using state-of-the-art software (FATIMAS, produced by nCode International Ltd).

Prior to undertaking the fatigue loading analysis on the main data records, sensitivity assessments were made of the data. Firstly, a fatigue analysis was undertaken on the 585 Hz data record; the record was then down-sampled to 12 Hz and the fatigue analysis repeated. This indicated that there was some chopping of some peaks at the 12 Hz sampling rate, and that a fatigue analysis on 12 Hz data would be accurate to within a factor of approximately 3 (a factor of 2 being typical for a rigorous fatigue analysis on ‘ideal’ data). A higher digitisation rate would therefore be preferable in any future monitoring, but when compared with the uncertainties over fatigue resistance, the 12 Hz data provided an acceptable basis for predicting fatigue loading. Secondly, data records for different bands of wind speed were investigated to assess relative contributions to fatigue damage. This was achieved by incorporating a fatigue damage curve derived from separate cyclic loading tests on the same design of lighting column. This showed that, as expected, there is a non-linear contribution to fatigue damage with respect to wind speed, there being far less at lower speeds than at higher speeds.

From these sensitivity analyses, a rational selection of data records was then possible which enabled an efficient fatigue analysis programme to be operated.

The data records were grouped according to mean wind speed into 7 bands, each of 2 m/s width: 4-6, 6-8, 8-10, 10-12, 12-14, 14-16, and 16-18 m/s, each band then being labelled according to its mid value (i.e., 5, 7, 9, 11, 13, 15, and 17 m/s). Selected runs were taken from each band, more being taken from the higher bands than from the lower (because of their greater fatigue loading significance). Each selected 30 min strain time history was converted to a stress time history and was cycle counted using a Rainflow Cycle Counting module within FATIMAS. The module was configured to gate the signal (i.e., to ignore cycles with peak-to-peak values below 5 MPa which removed background noise) and to apply a constant set of pre-determined bin constraints to the output cycles. These were: a bin width, or range, of 5 MPa, a range minimum of 5 MPa, a range maximum of 125 MPa, giving 24 range bins in total. The module gave stress cycle counts with respect not only to prescribed bin width, but also local mean stress (the mid value of the range of each cycle), these results being presented as 3-dimensional histograms (the axes being bin range, number of stress cycles counted, and local mean stress).

Fatigue damage produced by the cycle counts from each run was then calculated. The fatigue/endurance criteria for the critical welded shoulder joint just below the strain-gauged position (Fig. 1) had been derived from a series of fatigue tests carried out at The Welding Institute (Smith *et al.* 1999). The resulting design fatigue/endurance curve for this detail is shown in Fig. 8. A Goodman mean stress correction was used to account for the effect of mean stress levels, which is generally recognised to provide a conservative prediction of fatigue life. However, the mean stress levels were consistently relatively low and so not of particular significance in this data analysis. Material properties taken for the Grade 50C structural steel used for the lighting columns were an elastic modulus of $2.05.10^5$ MPa, a yield stress of 350 MPa, and an ultimate tensile strength of 500 MPa.

The output cycles from each data record relating to a given wind speed band were then summed

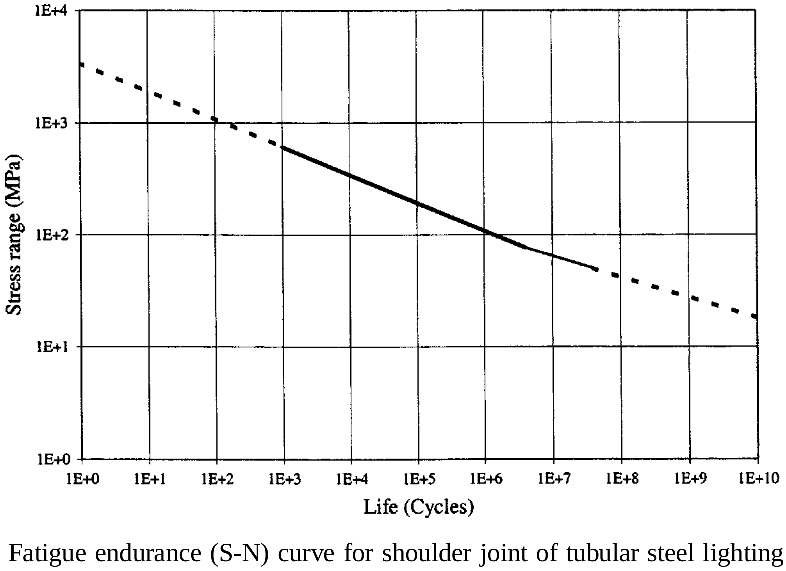

Fig. 8 Fatigue endurance (S-N) curve for shoulder joint of tubular steel lighting column

Table 1 Estimated fatigue lives for bolted and planted lighting columns

Wind speed (m/s)	Bolted		Planted	
	Damage/hr	Life (yrs)	Damage/hr	Life (yrs)
5	$2.2828.10^{-9}$	50000	$3.0858.10^{-9}$	36988
7	$5.0477.10^{-8}$	2261	$4.7749.10^{-8}$	2390
9	$1.4058.10^{-7}$	812	$1.0053.10^{-7}$	1135
11	$6.6928.10^{-7}$	171	$5.7039.10^{-7}$	200
13	$3.2283.10^{-6}$	35	$4.7143.10^{-6}$	24
15	$6.8233.10^{-6}$	17	$8.1242.10^{-6}$	14
17	$3.0232.10^{-5}$	3.8	$2.9239.10^{-5}$	3.9

across the bins and normalised back to cycles per hour (or per 30 mins) to provide a final, averaged, cycle count result for each wind speed.

The damage corresponding to these averaged results for each wind speed band was then computed afresh using Fig. 8 as described above. A summary of all the damage results and corresponding fatigue lives with respect to wind speed obtained from the averaged cycle counts is given in Table 1.

5. Fatigue life prediction

The relationship between life and damage is given by:

$$\text{Life in years} = \frac{1}{\text{Damage/hr}} \cdot 1.1414 \cdot 10^{-4}$$

where $1.1414.10^{-4}$ is 1 hr expressed in years, on the assumption that the given wind speed occurs continuously throughout the life of the column.

Clearly this is not appropriate in assessing the fatigue lives of these structures as they are subject to a range of wind speeds throughout their lives. To allow for this, the population of all wind speeds was represented by a Weibull distribution, using parameters which provided a close fit to the exceedance curve appropriate for the UK wind climate (BSI 1995). The parent distributions and cumulative distributions are given by, respectively:

$$\text{pdf} = ckx^{k-1}e^{-cx^k}$$

$$\text{cdf} = 1 - e^{-cx^k}$$

where parameter values are taken as $c = 12.99$ and $k = 1.85$ to represent the UK wind climate, and x is the ratio of wind speed to the 50-year return hourly mean wind speed for the site. The time, in hours, that any mean wind speed is exceeded, per year, is then given by 8766(1-cdf), where 8766 is the number of hours in a year.

As the highest mean wind speeds embraced in the measurements were in the 16–18 m/s range, it was necessary to extrapolate the results to predict damage under higher wind speeds. It was found that by plotting the damage/hr results against wind speed on a log-linear plot, a straight line was obtained (Fig. 9), and a linear extrapolation has been assumed. It is hoped to continue measurements at

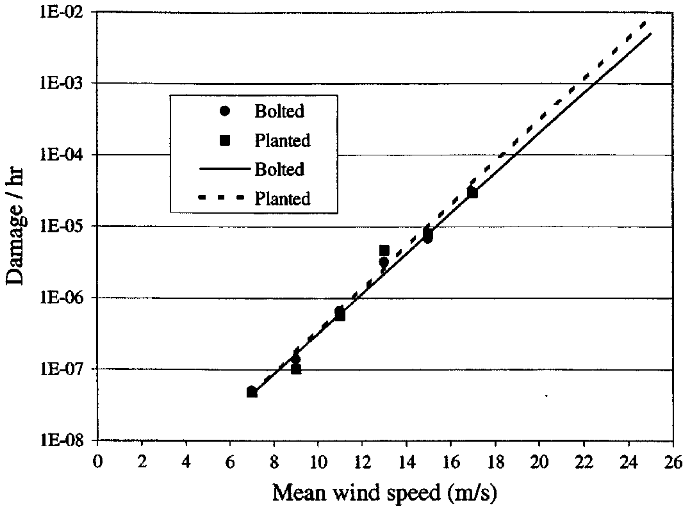

Fig. 9 Fatigue damage results as a function of wind speed

SRI to obtain results for higher wind speeds, or possibly to transfer the equipment to a more exposed site to improve the prospects of obtaining higher wind speed data.

The results for the bolted and planted columns are very similar. An approximate equation for the fitted lines in Fig. 9 is :

$$\text{Damage/hr} = 4.5.10^{-10}\, e^{0.66V}$$

where V is the mean wind speed in m/s.

Using the above procedure, the fatigue lives of the columns were calculated to be 240 years for the bolted column and 225 years for the planted column when erected at Silsoe in the south-east of England (i.e., based on an 50 - year return period hourly-mean site wind speed of 24.9 m/s).

These compare with a predicted fatigue life from the BD design document (Highways Agency *et al*. 1994) for the two columns when erected at Silsoe of about 200 years. However, if the *same* columns were to be erected on an exposed site in northern England where premature fatigue has been experienced (where the 50 - year return period hourly-mean site wind speed was 32.5 m/s), the fatigue life prediction would reduce to about 5 years for both column types (which was the age of the columns that had experienced fatigue cracking). For this case, the BD design rules predict a fatigue life of about 30 years if strict adherence is made to the static wind pressure in the relevant British Standard (BSI 1997). However, if due account is taken of the extreme exposure of the site where fatigue occurred, this prediction would reduce to about 7 years. The BD document would probably require columns heavier than the monitored columns on the more exposed site in order to meet the static wind loading requirements, but columns on such sites have, nonetheless, suffered premature fatigue. The fatigue rules in the BD document are contained in an Informative Annex in prEN 40 (CEN 1997) and so the present verification work has relevance in the future to lighting column design throughout Europe.

Whilst it is perhaps a little surprising that the fatigue life of the bolted, flange-plated column was not lower than that of the planted column - because the damping of the latter was higher - the difference is within experimental error. The clear result, however, is that low fatigue lives could be expected if such columns were erected on very exposed sites.

6. Drag coefficients and wind speed

Mean drag coefficients, C_d, were also determined from the strain records in order to investigate Reynolds Number effects. Data records of x-plane strains were selected for runs where the mean wind direction approached the luminaires within $\pm 20^o$ of the plane of the luminaires. The drag coefficient was calculated from the ratio of 'pressure' (taken as the mean wind dynamic pressure acting uniformly over the face area of the column above the strain gauged position which would produce the measured mean strain) to 'mean wind dynamic pressure' at the 10 m reference height. The presence of the luminaire was ignored in this exercise. The results are plotted in Figs. 10 and 11 for the bolted and planted columns respectively from where it can be seen that C_d values generally fall within the range 0.6-1.3.

The greatest uncertainty in the experimental values arises from uncertainty in the zero strain value,

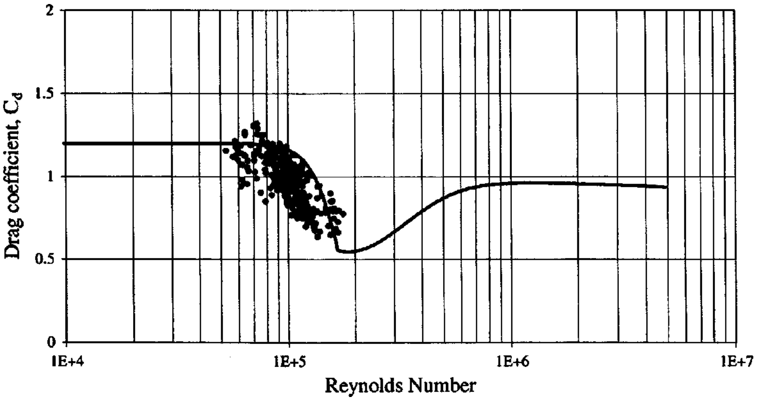

Fig. 10 Drag coefficients for bolted column and ESDU 80025 data

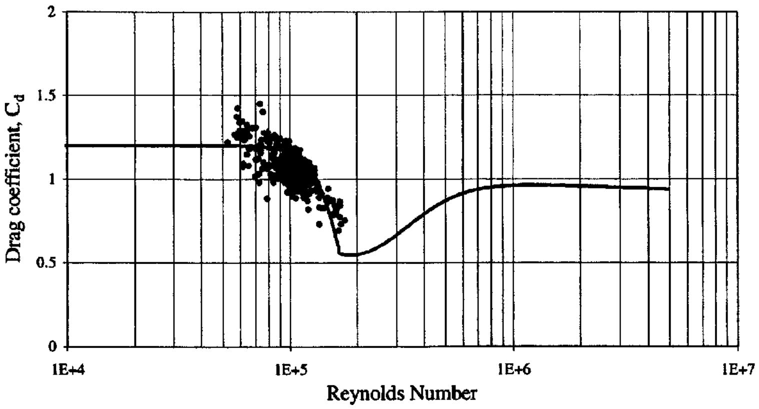

Fig. 11 Drag coefficients for planted column and ESDU 80025 data

which directly affects the mean strain value used in the calculation of the drag coefficients. The mean drag signal is small in relation to the peak fluctuations (typically less than 10%) which means that any error in the zero value will have a relatively large effect on the deduced mean value. Uncertainty in the zero strain value arises from the unavoidable constraint that a direct zero reading can be made only when there is no (or negligible) wind, which occurs infrequently and commonly at times well removed from when the drag measurements were made. Any temperature differences or zero-drift in the instrumentation electronics during the intervening period will tend to produce a false zero reading in relation to the drag measurements. Despite this, the data are reasonably well ordered. Also shown in Figs. 10 and 11 are the mean drag coefficient values obtained from ESDU 80025 (ESDU, 1980). The ESDU line is for a cylinder with an effective roughness height for the surface of 0.2 mm which is representative of the galvanised steel tube used for the lighting columns; this gives a surface roughness parameter of $1.4.10^{-3}$. The line has been corrected for the effect of turbulence according to the ESDU 80025 procedure taking the intensity and scale of turbulence values of 0.18 and 30 m respectively as given for ‘rural areas’ at 10 m above the ground. The resulting ESDU line gives a generally pleasing, close upper-bound estimate of the measured drag coefficients for both lighting columns.

7. Conclusions

The measurement project has provided valuable information and data on the behaviour of lighting columns in the wind. The values of damping are within the ranges specified in the BD design document and in prEN 40, and the natural frequencies are as expected for this form of column. Drag coefficients were also evaluated from the measurements as a function of wind speed, and these too were within the range of accepted design values.

The predicted fatigue lives suggest that whilst lighting columns of this form should generally have lives in excess of their design lives (usually 25 years), extreme care should be exercised at exposed, windy sites where fatigue performance could govern the design. Further fatigue loading data at wind speeds higher than the 17 m/s speeds recorded in this programme would be highly valuable to check the extrapolation used in this work, and to assess thoroughly the reliability of the existing BD document design rules.

A second programme of measurements is being conducted through 1999 and 2000 on 3 lighting columns. The planted column reported on here is serving as a base case and is being re-monitored; an identical column mounted in a resilient polythene sleeve housed in a cylindrical steel foundation unit is being monitored, and a 12 m tapered, octagonal folded-plate column is also being tested. All 3 columns have been strain gauged as reported here. A further refinement that has been introduced is the sampling of strains at 100 Hz instead of 12 Hz to improve the quality of the fatigue analysis. It is hoped that higher wind speeds will arise during the second programme of measurements as it is important to validate the design methodology over the full trans-critical Reynolds number range. The results of this second programme of measurements will be reported following completion of the testing.

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