The fatigue strength of high tensile steel wire cable subjected to stress fluctuations of small amplitude

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The Fatigue Strength of High Tensile Steel Wire Cable Subjected to Stress Fluctuations of Small Amplitude

Résistance à la fatigue de câbles de fil d'acier hautement stables sous l'influence de fluctuations d'effort de petite amplitude

Ermüdungsfestigkeit hochfester Stahldrahtkabel unter Einwirkung von Beanspruchungsschwankungen kleiner Amplitude

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This work was prompted by an interest in the fatigue strength of stranded wire rope in suspension bridge hangars, where the rope sustains a tensile load which is normally less than half the ultimate failing load and suffers proportionally small fluctuations due to the varying live loads on the bridge. Under these conditions a long life might be expected and so the investigation was concerned with a study of the fatigue life of the cable at the lower stress end of the *S-N* curve, and in particular with the determination of the endurance limit.

As the capacity of the available fatigue testing equipment was insufficient to test full size ropes, 0.6 in (15 mm) diameter concrete pre-stressing strand was used in the experiments. It consisted of seven 0.2 in (5 mm) diameter wires of ultimate tensile strength 112.2 tonf/in^2 (1730 N/mm^2), and had the advantage that its geometry was simple compared with a multi-layer rope, and the individual wires were large enough for strain measurements to be made on them reasonably easily.

The initial objective of the fatigue tests was to establish the *S-N* curve for this cable in fluctuating direct tension at a mean stress of 40 tonf/in^2 (618 N/mm) which was considered relevant to the bridge suspender application. The maximum practicable speed of 800 load cycles per minute was used for all the tests and, in all but the early tests, an electrical cut off device was fitted which stopped the test after the failure of one wire.

The first set of specimens, each about 24 in (610 mm) long, were made with

Table I. Specimens with coned white metal ends

a) Mean stress = 40 tonf/in^2 (618 N/mm^2)

	Stress fluctuation Semi-range r tonf/in^2 (N/mm^2)					
	8 (123)	7 (108)	6.5 (100)	6.3 (97)	6 (93)	5.1 (79)
Cycles to failure $\times 10^{-6}$	1.240 1.067 0.581	1.293	5.07	1.516 0.745	5.91 1.833	1.764 1.053

b) Mean stress = 70 tonf/in^2 (1080 N/mm^2)

	r tonf/in^2 (N/mm^2)		
	8.9 (137)	6.3 (97)	5.1 (79)
Cycles to failure $\times 10^{-6}$	0.197 0.300	1.023	1.025

coned white metal ends fitting special adaptor sockets which enabled them to be held in the Losenhausen testing machine. The results of these tests, which are shown in Table 1, indicate a shorter life than might have been expected. It was thought that this might have been due to corrosion caused by the flux used in making the white metal ends, as all the fractures occurred near the ends in the region likely to have been affected by the flux. Thus, although white metal ends were more relevant to the bridge rope problem, because of the possibility that the basic fatigue behaviour of the cable was being obscured, it was decided that some other device should be adopted for holding the ends.

The most satisfactory device devised consisted of a pair of plain half-round cylindrical steel collets about $3^1/_2$ in (90 mm) long which fitted around the cable and were separated from it by pieces of 16 swg (1.6 mm) half-hard aluminium shim, pre-formed to fit inside the collets. The collets were held in the standard wedge grips of the testing machine and the initial gripping was assisted by a small bush lightly welded to the end of the wire which rested on top of the collets, so pulling them into the grips. This bush was shown to play very little part in transmitting load and, in cases where the weld bead was broken in the initial gripping, the bush could be removed leaving the cable gripped wholly by the collets.

During the welding of the bushes a large aluminium block was clamped around the end of the cable to act as a heat sink minimising the heating of the cable. Care was taken to prevent any weld splash reaching the specimen after it has been demonstrated that a very tiny stray bead of weld had been the origin of a premature failure.

In all cases, and also with the specimens with white metal ends, failure occurred in one of the outer helical wires; in no case did a core wire fail. This same effect was observed by WARNER and HULSBOS [1] in tests on a similar 7-wire strand. The flexure of the helical wire as the tension load is applied to the cable causes local bending stresses which are about 7% higher than the average axial stress. Thus the range of stress variation for the helical wires is greater than that of the core wire and this, coupled with the residual stresses caused by pre-forming, might be expected to give them a lower fatigue life. However, measurements of strain indicate that, at the mean load used in the fatigue tests, the relative strain between the core and helical wires for a change of 1 ton (10 kN) in the tension was about 6×10^{-5}, and it is the fretting caused by this relative movement of the contacts between the wires that is the most probable cause of failure. Fretting will also occur between individual helical wires caused by flexure and consequent circumferential relative movement. Failures were seen to originate at the contacts between a helical wire and the core, between individual helical wires, and at the outside of the wires at the edge of the grips. No correlation between the fatigue strength and the type of failure was evident and a roughly equal number of specimens failed in each of the three ways.

No significant rise in temperature of the specimen was observed unless the test was continued after the first wire had fractured, when larger relative movements occurred.

The results of the fatigue tests on specimens with plain ends are shown in Table II. In analysing the data the results from the unbroken specimens were excluded and as only two specimens failed at 7.1 tonf/in^2 and three at 9.7 tonf/in^2 there was insufficient data for these two stress levels to be included.

Table II. Plain specimens

Mean stress 40 tonf/in^2 (618 N/mm^2)

r tonf/in^2 N/mm^2	7.1 (110)	9.7 (150)	11.1 (172)	12.5 (193)	13.8 (214)	15.2 (234)
N= Cycles to failure $\times 10^{-6}$	9.34* 4.57* 5.44* 4.87* 4.75* 6.62 4.20	11.16* 3.07 2.12 5.66* 5.37* 10.23* 1.37	1.23 4.37 0.706 2.56 8.02 11.4*	1.20 0.67 0.814 0.539 0.314 4.99 6.51*	0.382 0.821 3.16 0.347 0.354	0.412 1.33 0.283 0.142 0.429
$\log^{-1}(\log \bar{N})$	—	—	2.389	0.906	0.656	0.394

* Unbroken.

A mean value of $\log N$, where N is the number of cycles to failure, was taken for each of the remaining four stress levels and the equation of the mean line to fit this data was determined as

$$\log N = \frac{58.0593}{r} - 0.6423 + 0.1600\, r,$$

where r is the semi-range of the stress fluctuation in tonf/in² (or $\log N = \frac{896.6852}{r} - 0.6423 + 0.01036 r$ where r is in N/mm²). This curve is plotted in Fig. 1 which also shows the actual test results. Fig. 1 also shows the results for the cables with coned white-metal ends, already been referred to (Table I), which are shown to have a fatigue strength clearly inferior to those with plain ends.

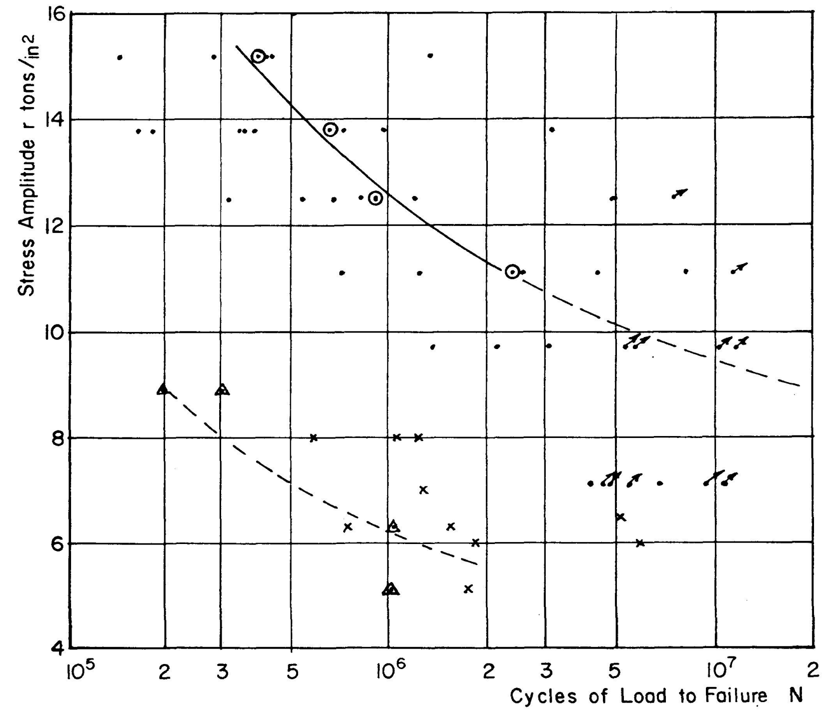

Fig. 1. Fatigue Tests on 7-wire Cable.

Key: • Plain ends, ⊙ $\log^{-1}\log \overline{N}$. White metal coned ends: × $\sigma_m = 40$ tons/in², △ $\sigma_m = 70$ tons/in².

The results are not readily comparable with those of previous investigations described by Tide and Van Horn [2], which include that already referred to [1] as these have used loading cycles with a constant lower stress and a varying upper stress and have been concerned with lives of up to the order of 2×10^6, i.e. much shorter than in this work. However, from the strength for a life of $N = 1 \times 10^6$ for a constant lower stress of 40% of the ultimate strength from reference [1] a simple linear Goodman relationship predicts a strength of 12.3 tonf/in² (190 N/mm²) at a mean stress of 40 tonf/in²

(618 N/mm^2), which is in good agreement with 12.6 tonf/in^2 (195 N/mm^2) at $N = 1 \times 10^6$ obtained from the mean line for these tests.

Fatigue data [3] on the wire of which the cable is made indicates an endurance limit at a mean stress of 40 tonf/in^2 (618 N/mm^2) of about 19 tonf/in^2 (294 N/mm^2), which is double that of the value for the cable (9.4 tonf/in^2 145 N/mm^2) predicted from the calculated mean line. Nevertheless this is a fluctuation of $\pm 23.5\%$ on the mean stress, which is very much greater variation of live load on dead load than might normally be expected in practice.

An estimation of the "safe life" for 90% and 99% of survivals with 50% confidence, is shown in Table III. It will be noted that the endurance in the first case is under one third of the mean endurance, and in the second, about a third of that.

Table III. "Safe Life" Estimation
(50% Confidence)

Stress Amplitude $\pm r$ tonf/in^2	r as % of UTS	Actual Mean Endurance $\times 10^{-5}$	Estimated Endurance $\times 10^{-5}$ % of Survivals	
			90	99
11.1	9.9	23.49	6.25	2.06
12.5	11.2	9.06	2.50	0.86
13.8	12.3	6.56	1.90	0.68
15.2	13.6	3.94	1.28	0.51

The large scatter of the results is probably due to variations in the conditions initiating fretting, which causes failure. These may arise from uneven roughness at the contacts due to rusting and from disturbance of the lay of the cable in the initial gripping causing unequal stressing of the individual wires and changes of the geometry of the contacts between them. Both are, however, variations which can be expected in practice.

A feature of the calculated mean line in Fig. 1 is the absence of any obvious endurance limit of stress, below which no further damage would occur. Some confirmation of the absence of an endurance limit is provided by the results of a small number of two-step loading tests given in Table IV. These show that for a semi-range of stress $r = 15.2$ tonf/in^2 (234 N/mm^2) the mean life with a preliminary loading of $r = 9.7$ tonf/in^2 (150 N/mm^2) is less than that with a preliminary loading of 7.1 tonf/in^2 (110 N/mm^2). In both cases the mean life is less than that for a one step test at the higher stress, indicating that some damage has been caused by the preliminary stressing, which might therefore be assumed to be above the endurance limit. The values of $\sum n/N$, shown in the right hand column of Table IV, ranging from 0.592 to 1.276 with an average of 0.948, give some indication of the probable accuracy of Miner's rule in a cumulative damage estimation in this case.

Table IV. Two Step Loading Tests

a) Step 1, $r_1 = \pm$ 9.7 tonf/in² (150 N/mm²); $N_1^* = 7.834 \times 10^6$
Step 2, $r_2 = \pm$ 15.2 tonf/in² (234 N/mm²); $N_2^* = 4.06 \times 10^5$

Specimen No.	Cycles of Load $\times 10^{-6}$		$\sum \frac{n}{N}$
	Step 1 n_1	Step 2 n_2	
1	5.663	0.233	1.276
2	5.373	0.196	1.152
3	0.172	0.237	0.606

Mean endurance at Step 2, $\text{Log}^{-1}(\log n_2) = 2.21 \times 10^5$.

b) Step 1, $r_1 = \pm$ 7.1 tonf/in² (110 N/mm²); $N_1^* = 466.7 \times 10^6$
Step 2, $r_2 = \pm$ 15.2 tonf/in² (234 N/mm²); $N_2^* = 4.06 \times 10^5$

Specimen No.	Cycles of Load $\times 10^{-6}$		$\sum \frac{n}{N}$
	Step 1 n_1	Step 2 n_2	
1	4.57	0.280	0.592
2	4.87	0.381	0.948
3	4.75	0.471	1.090
4	10.62	0.319	1.013
5	10.44	0.276	0.904

Mean endurance at Step 2, $\log^{-1}(\log n_2) = 3.38 \times 10^6$.

* Mean endurance from Fig. 1 for appropriate value of r.

Where fatigue failure results from surface cracks initiated by fretting – as in the cables tested – it has been shown [4] that there is a marked reduction of fatigue strength, and that the dominant parameters were the range of slip in the fretting area and the mean stress. Under fretting conditions the fatigue strength of a 100 tonf/in² (1540 N/mm²) steel, at a mean stress of 40 tonf/in² (618 N/mm²), could be reduced to ± 3 tonf/in² (45 N/mm²) for 3×10^7 cycles. Some fatigue damage was nearly always found to result from fretting with a slip range of a few ten thousandths of an inch which would lead to a reduced fatigue strength in subsequent higher loadings, even without fretting.

Although the fretting conditions in which the above results were obtained were not identical to those in the wire cable, and the composition of the steel was different, it is reasonable to conclude that the same principles apply and that small fluctuations of stress in the cable will cause fatigue damage, the effects of which must be taken into account in any cumulative damage assessment.

The importance of these small stresses in such a calculation is the probability of there being a much larger number of occurrences of them in a given period of time than of the higher stresses. The loads at the lower end of a traffic loading spectrum have a larger frequency of occurrence than the larger ones. Vibrations, such as are excited by the wind, are also likely to cause a large number of low amplitude stress variations; an oscillation of frequency 14 Hz, for instance, existing for only 200 hours per year will accumulate 100 million cycles in ten years.

The conclusions of this investigation are that, for the stress levels examined, there is no lower value of the stress fluctuation below which failure of the cable will not occur in less than ten million cycles, and that it is not safe to assume endurances greater than this for other lower, stresses.

Notation

n	Number of cycles of loading applied.
N	Number of cycles of load to cause failure.
$\bar{N}$	Mean value of N for several specimens.
r	Variation of the applied stress about a mean stress.
UTS	Ultimate tensile stress.

Note: The S.I. equivalents to the values in British units have been rounded off.

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Summary

In the fatigue tests described the cable was subjected to comparatively small stress fluctuations about a mean stress approximating to the dead load stress appropriate to a structural application. Fatigue failure was caused by fretting at a stress lower than the fatigue strength of the wire of which the cable was made and, for the ranges examined, there was no endurance limit.

Résumé

Dans les tests de fatigue le câble était soumis à des fluctuations d'effort relativement petites autour d'un effort principal approximatif à l'effort de charge qui est attribué à une application structurelle. Des fautes de fatigue étaient causées par le frottement à un effort inférieur à la résistance de fatigue des fils dont le câble était composé. Pour le domaine examiné il n'existait pas de limite d'endurance.

Zusammenfassung

In den beschriebenen Ermüdungstests wurde das Kabel verhältnismässig kleinen Beanspruchungsschwankungen um einen Hauptbeanspruchungswert herum ausgesetzt, welcher annähernd der Traglastbeanspruchung in der baulichen Anwendung entspricht. Ermüdungsfehler entstanden durch Reibung bei einer Beanspruchung, welche kleiner war als die Ermüdungsfestigkeit der Drähte, aus denen das Kabel bestand. Für den untersuchten Bereich bestand kein Dauerhaftigkeitsgrenzwert.