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Effects of Length on Fatigue of Steel Wires in Service

Effets de la longueur sur la fatigue des fils d'acier en service

Einfluß der Länge auf die Betriebsermüdung von Stahldrähten

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SUMMARY
Practical issues in relation to the fatigue of 5 mm wires, 7-wire prestressing strand, and hanger cables, are discussed. Examples are given of failures taken from bridges in service.

RÉSUMÉ
L'article traite de questions pratiques intéressant la fatigue des fils métalliques de 5 mm, des torons à précontrainte á 7 fils et des câbles de suspension. Il présente des exemples de défaillances constatées sur des ponts en service.

ZUSAMMENFASSUNG
Praktische Fragen in bezug auf die Ermüdung von 5 mm-Draht, 7-drähtigen Spannlitzen und Hängekabel werden diskutiert. Beispiele von Ausfällen an in Betrieb stehenden Brücken werden angeführt.

1. INTRODUCTION

Steel wires are used in bridge engineering for prestressed concrete beams and in cables for suspended and stayed structures. The wires are normally used as assemblages, for example as 7-wire prestressing strand, and as cables. There are a variety of types of prestressing strand but the most common form in current practice is 7-wire strand composed of a central 'king' wire having six wires helically wound around it with a lay length of between 12 and 18 times the nominal strand diameter. Suspension and stay cables are supplied in a number of configurations to suit the requirements and preferences of the designer. Typical types of cable configuration are: helically wound locked coil, multi strand, and parallel wire bundles. Sizes of the constituent wires are typically in the range 2 to 7mm diameter.

In the technical development of wire and strand the mechanical properties that have received most attention have been the breaking load, ductility and stress relaxation. Fatigue performance has received less attention and until recently has been treated as a secondary issue of little practical importance. In consequence fatigue testing has been carried out to variable standards and one of the few available recommendations to be published is by RILEM [1]. Here, it is recommended that for bars and wires the free length between grips should be at least 500mm. For strand it should be five times the lay length or 700mm. The cyclic testing frequency should be in the range 1.33 to 100 Hz but it is stated that 3.33 to 10 Hz is preferable. Control tests should involve at least six specimens. Failure of strand can be taken as fracture of one wire; no account should be taken of tests having fractures located within five strand diameters of the grips.

In practice many investigations have failed to meet the RILEM recommendations. Indeed they are quite difficult to meet because few commercially available fatigue testing machines have suitable load ranges in combination with headrooms that will accommodate a specimen 500mm long plus special grips, let along 700mm. The gripping of wires and strands presents special problems which investigators have tackled in different ways but it remains quite difficult to avoid fractures within five strand diameters of the grips.

Engineers' attitudes to fatigue of wires have changed in recent years. This is partly as a result of fatigue failures that have occurred in service; in Germany prestressing tendons were found to have failed in fatigue at mechanical connections in a curved concrete box girder bridge and similar cracks were found in numerous other bridges as described by Sieble [2]. The CEB Model Code [3] has introduced fatigue clauses giving design assessment procedures and recommended fatigue strengths for prestressing steel. The properties and performance of different types of prestressing steel have been summarised by Mallett [4].

This paper deals mainly with fatigue of 5mm diameter steel wires in relation to some of the practical issues facing engineers responsible for designing and maintaining highway bridges. Data are drawn from several laboratory investigations in support of specific bridge investigations and are not from a single coherent programme.

2. PERFORMANCE OF SINGLE AND MULTI-WIRES

Length effects are of course the subject of this conference and it is generally understood that fatigue performance of wires reduces with increasing length; endurances for free lengths of 900mm are said to be some 20-50 per cent lower than for 250mm lengths depending on the value of mean stress. Investigators are aware that it is essential to test adequate free lengths, but as mentioned in Section 1, are often constrained by the dimensions of available testing machines. Leaving aside the dictates of scientific enquiry the practical reason for testing adequate lengths is to ensure that realistic lower-bound performances are obtained. In this context it should be noted that the performances usually quoted are for uniaxial tests carried out on free lengths of wire or strand in air. However, prestressing strand behaves differently when embedded in concrete and it is more relevant to test beams subjected to bending fatigue. In tests by Howells and Raithby [5], on prestressed lightweight aggregate beams of 15.4m length loaded under 4-point bending, the prestressing wires failed in fatigue after 0.289 million cycles (see fig 1). Interestingly some of the wires failed at more than one place along their length. When the beam was demolished after the test, a number of pieces of wire, about 500mm long and having fatigue fractures at each end, were lifted out of the prestressing strand. This indicates that although the wires were broken in one place they were able to pick up load a short distance from the fracture face and incur a second fatigue failure. Thus it is evident that there is a different regime affecting the length effect for wires embedded in concrete.

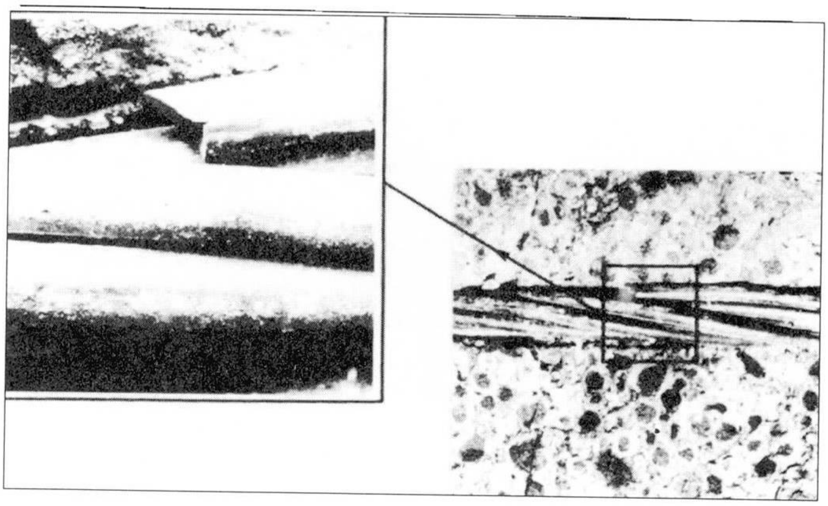

Fig 1 Fatigue fracture of prestressing strand in lightweight aggregate concrete beams.

In a series of investigations of highway bridges, axial fatigue tests were carried out in air on wires, strands and cables having free lengths of 160 to 2800mm. Failures were classified as when one wire in a strand had failed and when five wires in a cable had failed. Unfortunately the experimental conditions were dictated by the individual investigations so that there were too many variables to enable length effect to be commented on in any detail.

As part of an investigation of the collapse of Ynys y Gwas Bridge by Woodward [6], fatigue tests were conducted on samples of 5mm prestressing wires removed from the bridge. Many of the wires had fractured before the bridge collapsed and it was necessary to check whether fatigue had occurred. In the event the fracture surfaces were spoiled by corrosion and immersion in the river beneath the bridge and it was not possible to identify the mechanism of failure. Fatigue tests were conducted on wires selected as being (a) in pristine condition and (b) different degrees of corrosion. In these tests the free length between grips was 160mm ie 32 diameters. There was an emphasis on obtaining long endurances.

The fatigue data are shown in fig 2 where they are compared with data for 7-wire strand tested with a free length of 300mm. It is evident that the single wires exhibited slightly better performances at endurances beyond one million cycles but the difference was not as significant as had been anticipated, bearing in mind that the strand was tested in longer free lengths and furthermore there was the likelihood of fretting causing earlier initiation. The results are consistent with tests reported by Fisher and Viest [7] which indicated that wires can have higher fatigue strengths than strand.

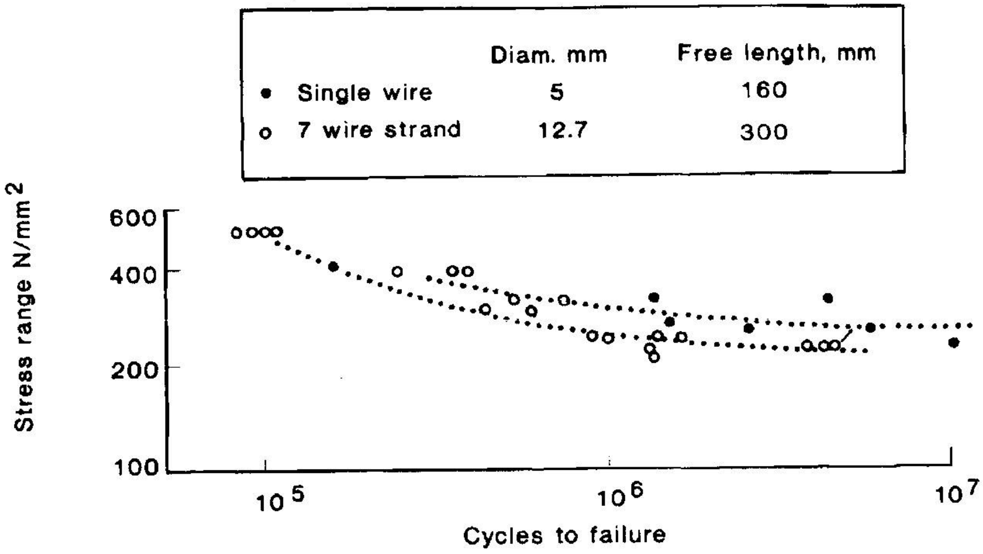

Fig.2 Endurances of single wires and strand

The data for the strand are compared with data from two other investigations involving tests on free lengths of 500 and 2800mm in fig 3. In this case there is

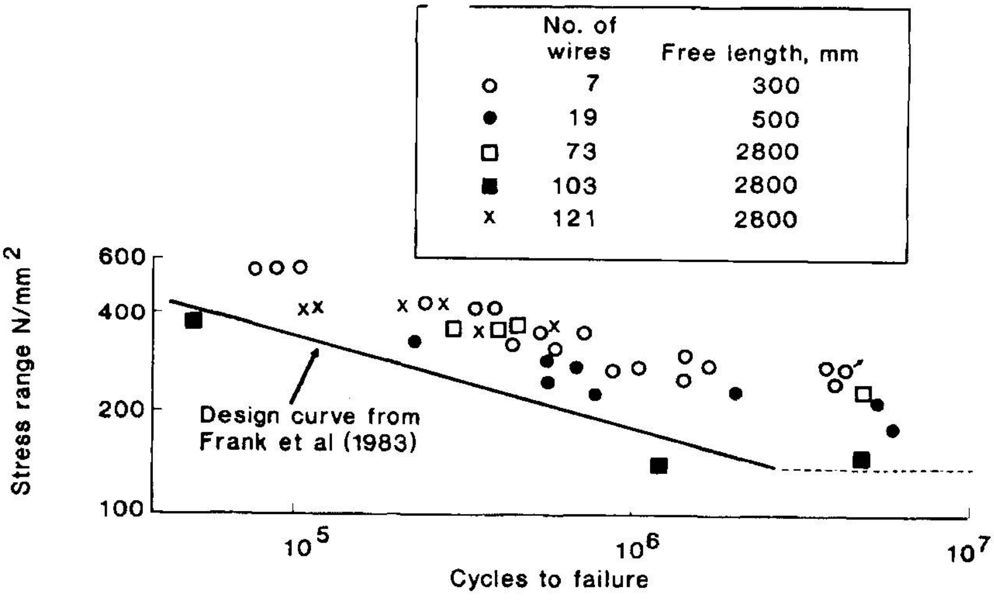

Fig.3 Endurances of strands and cables

a tendency for the tests on specimens having longer free lengths to exhibit lower performances. There was evidence of fretting in the 19-wire strand and the cables. The cables were tested with sockets fitted and failures were always in the vicinity of the socket. However, performance correlated surprisingly well with other work where failures occurred in the middle of the free length, Tilly [8], but the behaviour shown in fig 3 may be unrelated to the longer free length.

Comparatively little attention has been given to establishing performance curves for wires and strands. In one of the few comprehensive investigations Paulson, Frank and Breen [9] analysed available data for 7-wire strand and produced a recommended lower bound curve as shown in fig 3. It can be seen to correlate satisfactorily with the data in this paper.

3. CORROSION

The remnant fatigue strength of severely corroded wires and strands was investigated for samples removed from highway bridges after 16 to 21 years in service. The stress ranges were corrected to net values at the failed sections so that performances could be assessed on factors other than the loss of load bearing section.

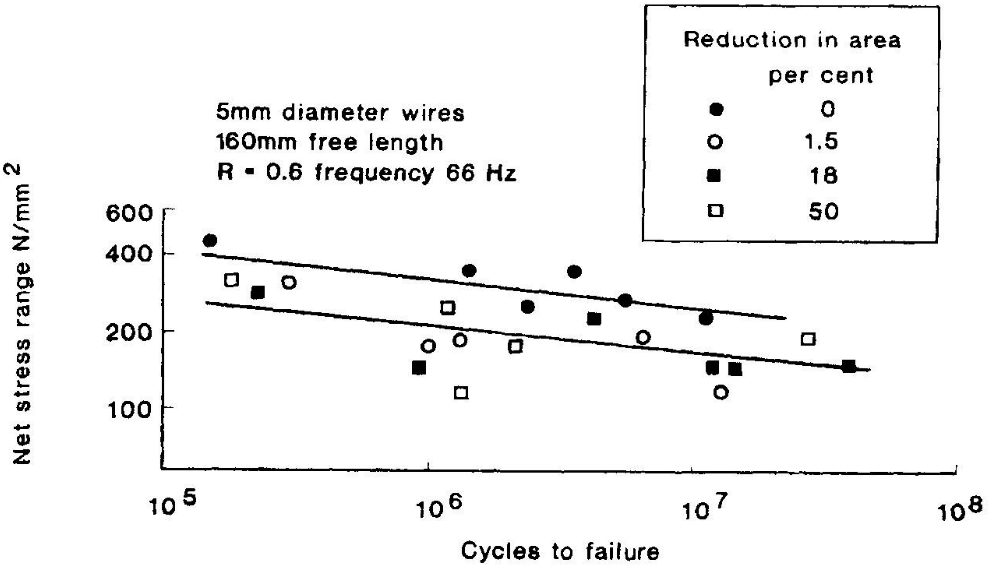

Fig.4 Endurances of corroded wires

For the single wires removed from Ynys y Gwas bridge there were losses in section of up to 50 per cent. The wires were classified into three levels of corrosion as shown in fig 4. It was evident that there is no apparent relationship between the extent of corrosion and reduction in fatigue strength. The overall reduction in lower bound net strength is about 50 per cent.

For the 7-wire strand there were fewer specimens and it was not possible to classify corrosion damage in the same way as for the single wires. The losses in section were 5 to 15 per cent but very badly corroded sections having more than one wire broken were excluded. It was found that the reduction in lower bound fatigue strength, shown in fig 5, is about 35 per cent. There were fewer tests and less experimental scatter than for the single wires and if more tests had been conducted the overall reduction might have been as much as for the single wires ie 50 per cent.

These results are compatible with the earlier investigations by Neubert and Nurnberger [10] who investigated the effects of depth of pit in smooth bars and reported reductions in fatigue strength of up to 60 per cent for pits 1.25mm deep. Erdmann, Kordina and Neisecke [11] tested prestressing steel removed from demolished structures. They found reductions in strength of up to 50 per cent caused by corrosion pits up to 0.25mm deep but were unable to establish a relationship between fatigue strength and depth of pit.

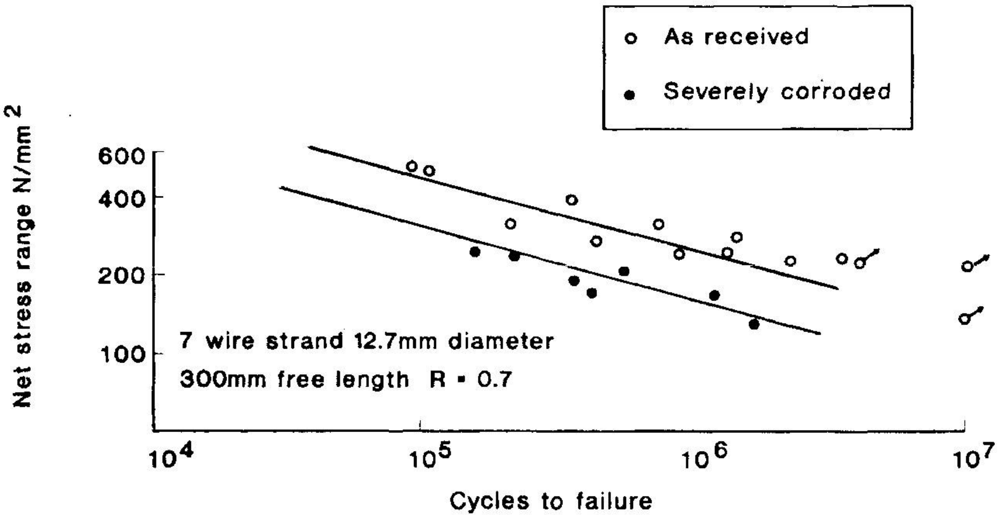

Fig.5 Endurances of corroded prestressing strand
(Strands removed from structures after 16-21yr)

The lack of correlation between fatigue performance and pit depth, and between loss in section and performance, may be explained by the order of magnitude difference between the number of cycles to crack initiation and the number in propagation. If a relatively small pit depth is sufficient to eliminate the initiation stage, so that most if not all of the endurance is in propagation, then a deeper crack will merely reduce the remnant life by a little more. In consequence the different performances for various pit depths are likely to be relatively small and most probably masked by experimental scatter.

Corrosion almost certainly influences length effect because the statistical distribution of corrosion pits is likely to be different from the distribution of flaws present in the surface of uncorroded wires. There is no information currently available on length effects under these circumstances.

4. FRACTURE TYPES

It has been estimated that a smooth defect free wire should have a fatigue endurance limit of about 360 N/mm². However, typical wires in service are not free of defects and the 'as received' 5mm wires tested by Woodward [6] exhibited a fatigue stress range of about 220 N/mm² at 10 million cycles. Typically, the fatigue cracking is initiated at a defect on the surface and propagates on a plane at 90° to the longitudinal axis of the wire, until the section is no longer able to support the maximum cyclic stress and final fracture takes place, see fig 6.

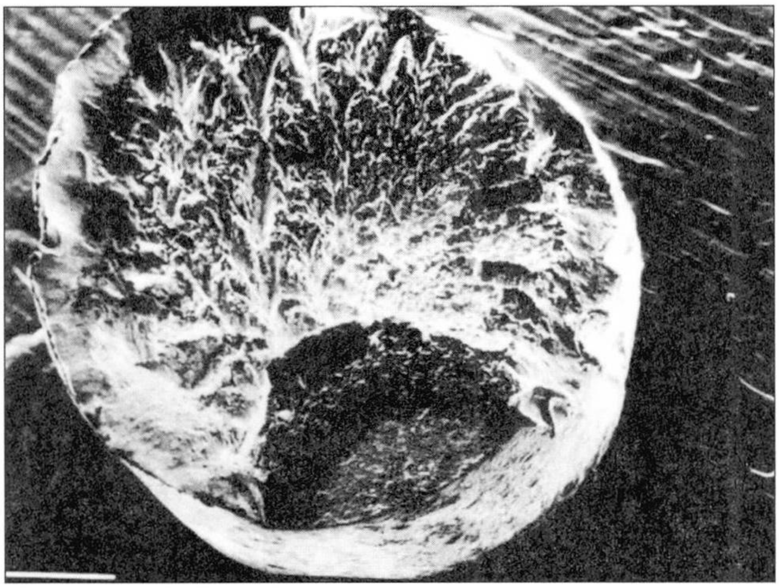

Fig 6 Fatigue fracture of 5mm wire.

The final fracture may be on a plane inclined to the longitudinal axis or may be brittle type; both types occurred in these investigations. Other types of fracture that can occur include cracks initiated at fretting sites, at corrosion pits, and corrosion fatigue.

4.1 Fretting

The nature of strands is such that when they are tested under tensile loads relative movements occur between the spirally wound outer wires and between the outer and inner wires. This causes fretting at the points of contact between the wires leading to earlier initiation of cracks and reduced fatigue lives as discussed for 7-wire strand by Cullimore [12]. In the present investigations fretting induced failures were identified in tests on the 19-wire strand - see fig 7. It was most dramatically exhibited on the larger cables tested in a specially designed bending regime as shown in fig 8, Tilly [13].

Fig 7 Fretting fatigue in 19-wire strand.

For fretting fatigue the length effect is related to the lay length of the strand or rope.

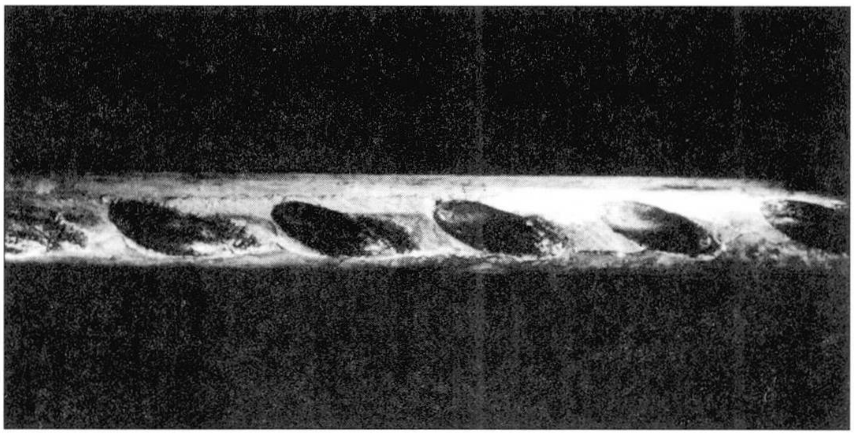

Fig 8 Fretting damage on 5mm wire from hanger cable.

4.2 Corrosion pits

As described in section 3 corrosion causes up to 50 per cent reduction in remnant fatigue strength due to the presence of pits causing local stress concentrations. Examples of fatigue initiated from corrosion pits are given in figs 9 and 10. Here the pit depths were about 0.8mm and 0.34mm respectively and are fairly typical of the more severely corroded wires. Final fracture of the 8mm diameter wire shown in fig 10 is brittle type.

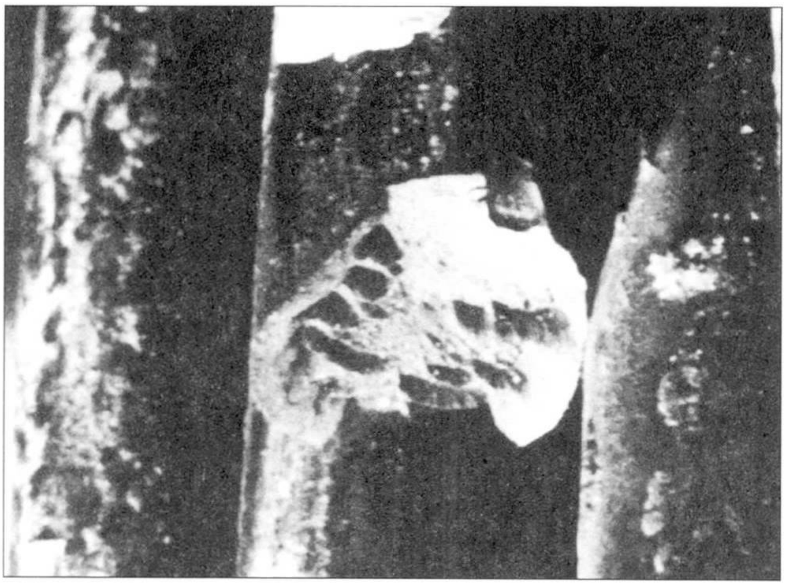

Fig 9 Initiation from corrosion pit in 19-wire strand.

The fatigue strength of corroded wires removed from a structure is a measure of performance which is useful for assessing remnant strength of structures but is not necessarily a correct simulation of the mechanics of corrosion and fatigue in practice. This is because corrosion and fatigue are interactive processes, as illustrated in the next section.

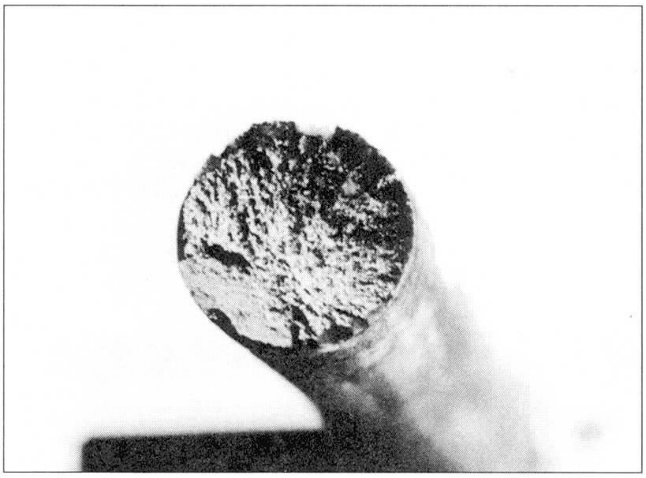

Fig 10 Initiation from corrosion pit in 8mm diameter wire.

4.3 Corrosion Fatigue

An example of corrosion fatigue occurred in galvanised wires removed from the hanger cables of a suspension bridge after some 10 years in service. The cables are believed to have experienced higher load ranges than had been anticipated and wires were found to have fractured close to the sockets where there was a combination of high stress and corrosive conditions. The cables were subsequently replaced by larger diameters and an improved design of socket was used.

Fractures of the wires took place in two stages; initiation represented by a flat region at 90° to the axis of the wire, and the final shear failure represented by a fibrous region inclined to the axis, see fig 11. Numerous fatigue cracks developed in the soft zinc coating, some being deflected along the zinc-to-steel interface, and some propagated into the steel. A longitudinal section through a

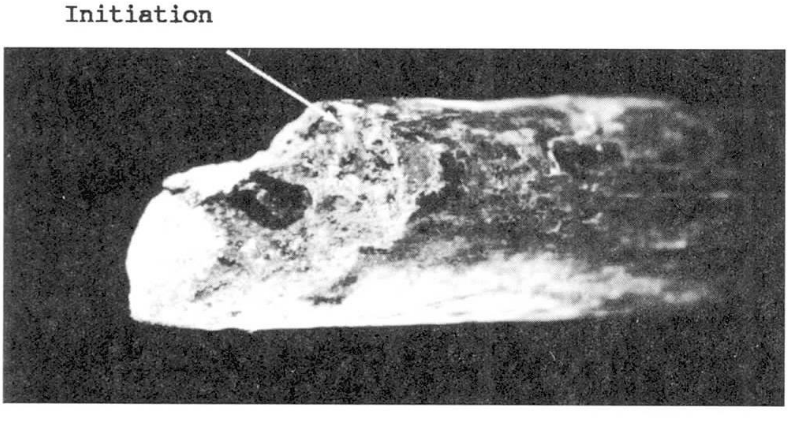

Fig 11 Corrosion fatigue failure of 3.4mm diameter wire after 10 years' service.

corrosion fatigue crack which did not lead to fracture is shown in fig 12 and it is evident that propagation was slow because there had been enough time for oxidation to occur. The longitudinal characteristics of the crack are typical of numerous others that were sectioned and are a reflection of the directional nature of the metallurgical properties of wire. It appears that there has been laminar splitting of the fibrous microstructure leading to lateral oxidation. In this example the crack appears to have initiated from the bottom of a corrosion pit which was about 0.2mm deep but there is no certainty because continued corrosion on the surface of the wire is likely to have changed the surface topography.

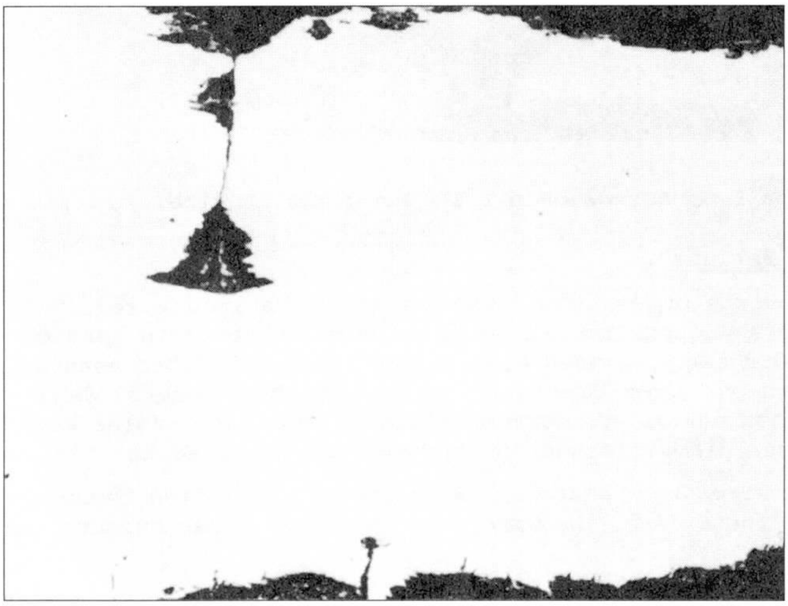

Fig 12 Corrosion fatigue crack adjacent to final fracture.

5. CONCLUDING REMARKS

A number of practical issues in relation to fatigue length effects have arisen through testing work in support of case studies of highway bridges.

It is important to test long sample lengths so that realistic lower bound fatigue strengths can be obtained. However it is not always possible to use suitable testing machines and there is a need to have more rigorously applied standards of testing.

In practice the length effects exhibited by single wires are likely to be modified in service conditions because wires are rarely used singly and are usually in 7-wire strand for pre-stressed concrete or as spirally wound cables for stays and suspenders. Parallel wire bundled cables are not considered in this paper. In strands and cables, initiation is dictated by the action of fretting and is therefore more dependent on lay length than on the statistical distribution of surface flaws. Corrosion can occur in service and influences the fatigue process through pits from which initiation can occur and by interacting with the crack propagation ie corrosion fatigue. Under corrosive conditions the length effect is likely to be dependent on the development and distribution of pits.

When prestressing strand is embedded in concrete the length effect is modified because of the transmission length between the concrete and steel. It is possible for wires to fracture but pick up load and fracture in a second position only 500mm or so from the first point. Work on reinforcement bars has shown that fatigue endurances in concrete are longer than in air and fracture locations are dictated by the disposition of cracking in the concrete rather than the presence of flaws on the surface of the steel. Although less comparative testing has been done on prestressing steel, it seems that the same situation applies and fractures coincide with cracks in the concrete.

ACKNOWLEDGEMENTS

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