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A New Small Sample Test Configuration for Fatigue Life Estimation of Overhead Contact Wires

Özgün Sunar[1], **David Fletcher**[2]

[1]Department of Railway Systems and Technologies, Eskisehir Technical University, Eskisehir, Turkey

[2]Department of Mechanical Engineering, University of Sheffield, Sheffield, S1 3JD, UK

Abstract

Fatigue in railway overhead line electrification (OLE) contact wires can cause sudden catastrophic failures. The contact wire interacting with the pantograph both mechanically and electrically is subjected to tension and repetitive bending due to the pantograph contact force. Recently, fatigue failures of OLE have risen in prominence with increases in train speed. To address this a new fatigue test configuration has been developed. The study focuses on a method for testing the wire as a component enabling fatigue life evaluation of worn wires, or exploring the effect of installation damage, through component level evaluation of crack initiation and propagation. The new test configuration places a 400mm-length contact wire in a combination of bending and pretension with realistic boundary conditions replicating service conditions for longer spans. The results are presented in a strain-life format to provide data for a wide range of potential service conditions.

Keywords: contact wire, overhead lines, fatigue testing machine, pantograph-contact wire interaction

1. Introduction

Overhead line electrification (OLE) is used for transmitting energy to trains by using a contact wire interfacing with a pantograph and collector strip on the train. In a typical configuration the contact wire is supported by auxiliary wires and also a tensioning mechanism to ensure a level contact wire with limited dynamic deflection thereby promoting good current collection quality. The pantograph and contact wire interaction is both a mechanical and electrical system. While the electrical transmission occurs at their interface the pantograph exerts contact force on the contact wire with the aim of maintaining the physical contact. Although the pantograph is designed to ensure steady contact force factors including surface irregularities of the contact wire, OLE fittings and dynamic

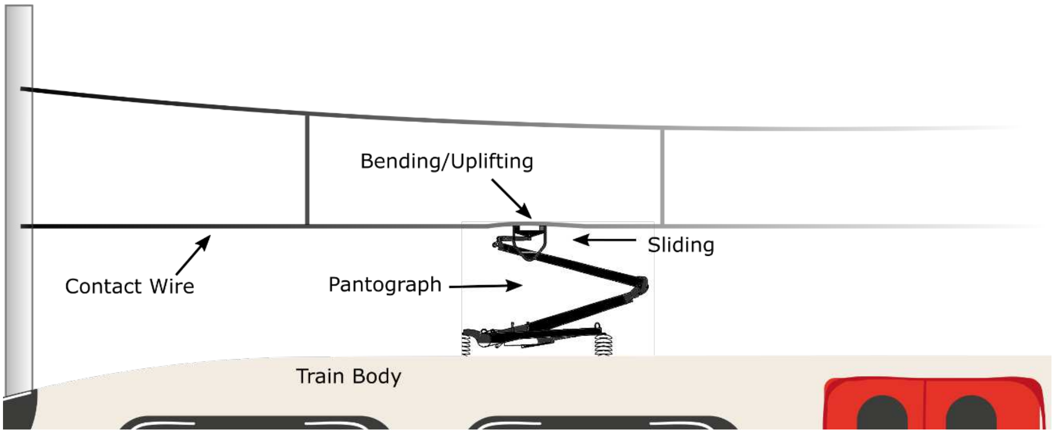

Figure 1 Schematic of OLE system. Regions of most extreme bending close to the pantograph interface are exaggerated for clarity.

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interactions while passing structures such as low bridges or small-bore tunnels can result in fluctuations in the contact force. Figure 1 shows schematically the contact wire and pantograph interface.

The contact wire plays a vital role in reliability of OLE systems. Therefore contact wires are often replaced at between 30 and 50 years due to the sliding wear [1]. Additionally, OLE dynamics, contact wire gradients and contact wire irregularities also can play an important role in determining service life, particularly due to the accelerated surface degradation of the contact wire [2], [3]. However, recent reports and studies showed that fatigue is also a significant limiting factor in determining the service life of OLE systems in particular for railway lines with trains running at high speed [4], [5]. The main reason for fatigue in contact wires is that the pantograph exerts vertical contact force which causes repeated bending in the contact wire. The fatigue failures of OLE can lead to sudden failures (in contrast to the progressive process of wear) and disruptive delays. The prevention, particularly of these sudden failures, plays an important role in improving railway performance.

In the past the problem of wear was viewed as the primary issue because failures due to wear occurred before other prospective mechanisms, i.e. wear was the system life limiting process. However, in recent years, the increase in train speed has resulted in higher contact force fluctuations [6], [7]. A growing number of studies have shown that bending fatigue of contact wire has become a significant issue to be taken into account for OLE safety [8], [9]. In existing work the vast majority of studies on fatigue in the contact wire have been experimental. Sugahara et at. [10] carried out a number of experiments on fatigue life estimation for overhead contact wire with a servo motor configured to apply oscillating force to contact wire. Similarly, fatigue life estimation of contact wires was conducted by Yamashita et al. [11] in which bending of hard drawn copper contact wire was conducted by adjusting a crank and motor. Zhen et al. [6], [12] investigated the bending fatigue life of cold drawn and CuMg contact wires combining experimental and finite element analysis. These studies suggested that an S-N curve method can be used for predicting the fatigue live of contact wires, with the experimental configurations requiring a specimen of 2-3 metres length to conduct the fatigue testing.

Regarding the bending stress in the contact wire due to the contact force, Kim et al. [13] highlighted that the uplift displacement was directly related to the bending strain of the contact wire and the contact force was the most important factor in determining its fatigue life. To broaden this knowledge, Sunar [14] conducted research to establish a correlation between contact force and bending stress/strain in the contact wire by using inspection data collected from UK mainline railway equipped with “Series 1” OLE [15]. Combined with finite element modelling this showed that depending on the configuration and OLE fittings used the maximum strain in the contact wire could reach the elastic limit of the material when contact force increased from the typical design operating condition of 100 N to a peak of 300 N bringing the potential for permanent plastic deformation.

On the question of whether other factors exist to initiate fatigue in the contact wire, a small scale study by Massat et al. [16] found that defects on the surface of the contact wire due to pantograph friction, electrical arcs and corrosion could cause crack initiation and increase the risk of fatigue failure. Sunar et al. [14], [17] examined existing contact wires extracted from a mainline and conducted laboratory tests with contact wire samples to determine whether arcs have the potential to initiate fatigue damage in the contact wire. Their results identified defects including voids beneath the surface of the contact wire in areas subject to arcing that significantly reduced total fatigue life. Furthermore, there is evidence about potential effects of OLE fittings on the fatigue life of contact wires, for example from Network Rail [18] reporting that a rapid fatigue failure occurred in the contact wire at the entry splice just two years after the installation. In the same vein, Nguyen et al. [19] investigated a fatigue crack observed near a junction claw. In their study the crack initiated from the bottom (worn surface) of the contact wire and propagated through the section with final failure at the contact wire top surface. These incidents indicate that fatigue fractures in the contact wires can be very rapid as pantograph contact force acts in combination with line tension and stress raising factors such as surface defects, arc events, and OLE fittings.

Fatigue is a phenomenon which is often explored by tests on standard specimens. However, quantifying the fatigue performance of the material alone is insufficient given the number of factors which may affect contact wire life. Hence, special purpose fatigue configurations are often found more representative, for example using the original geometry of the contact wire. A constraint in design of such tests is that although samples short relative to wire lengths in railway installations were used in the literature, previous test methods still required contact wire specimens in the order of 2-3 metres length. Furthermore, in almost all the test configurations identified in the literature single contact and three-point contact bending configurations were used. A three-point bending arrangement is quite poorly suited to assess fatigue performance of contact wires with surface defects since the defect and the location of maximum stress may not be co-incident making interpretation of the outcome complicated. More useful is to explore a length of wire under load allowing the location of crack initiation and growth to emerge during the test rather than being induced at the point of load application. In the study reported here a test configuration was developed to determine the fatigue life of contact wires with realistic boundary conditions. The new fatigue test configuration can examine the fatigue behaviours of the contact wire samples under cyclic loads at a component level rather than an abstracted material level. It is designed to capture the key aspects of contact wire testing (line tension combined with bending and potentially additional features such as worn or pre-damaged wires) while retaining the benefits of using a small sample size.

2. Methods

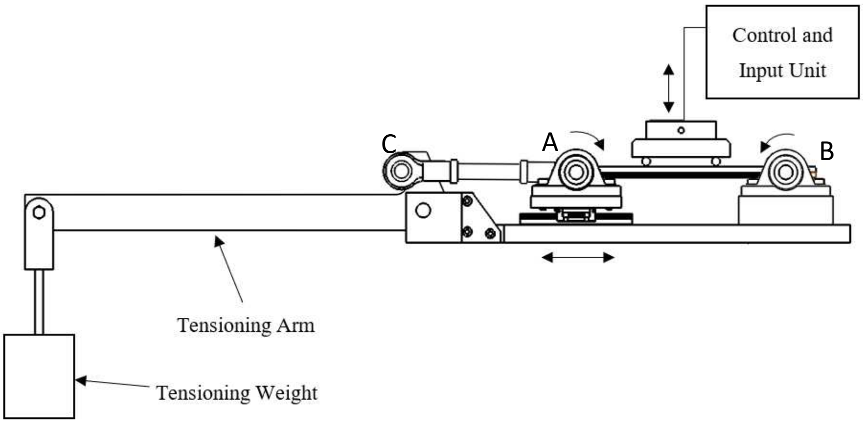
2.1. OLE fatigue apparatus

The test configuration is shown schematically in Figure 2a and in the photograph Figure 2b. It is designed to test a 400mm length of contact wire loaded between pivoted clamping blocks A and B. This provides a simply supported configuration to allow bending to which tension loading can also be applied. The axial tension in the contact wire is applied through a tensioning arm providing a 10:1 force ratio at point C. Linear guides placed underneath pivot housing A allow linear movement of the contact wire while it is horizontally constrained by a clamp on the side furthest from load application at pivot B. Transverse movement of the pivots is fully constrained to ensure the wire is held in a two-dimensional force-displacement system.

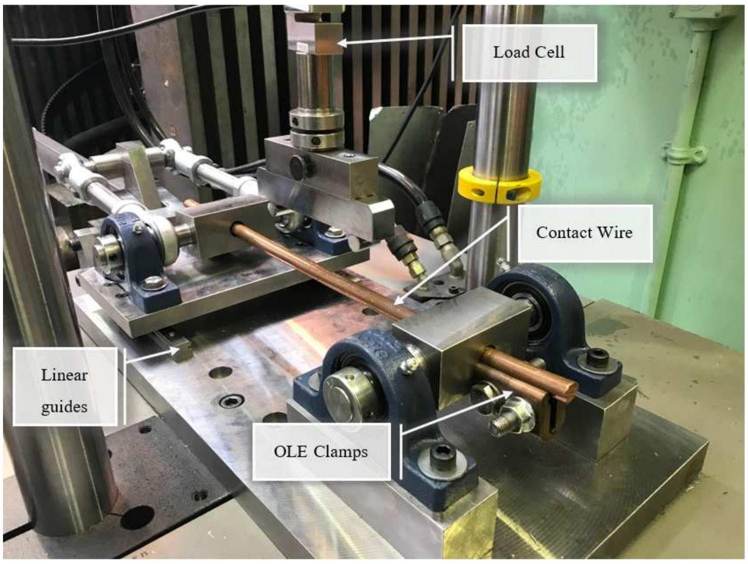
According to the method of four-point bend testing (ASTM D6272-10 [20] the working section of the sample between pivots A and B is divided into three equal lengths with the vertical bending force applied from two equally distributed points. This arrangement provides a uniform moment distribution across the middle span of the contact wire sample rather than a single high-peak at the point of load application in three-point bending. The live sample length between pivots A and B is 300 mm.

The apparatus was designed to be mounted in an Instron 8511 25kN capacity test machine which supplied the actuator and control system for vertical movement. In the current work this was driven with a sine wave motion, but under computer control could equally be driven to apply more complex time history data adapted from field measurements or modelling predictions.

The vertical load was measured using a load cell with 5 kN capacity (RLT0500, RDP Group) installed between the actuator and four-point bending fixture. Load and displacement in the tests were monitored and controlled using a MOOG modular test controller interfaced to a PC for data logging. The load-cell and displacement transducer were calibrated prior to testing, and experiments were automatically terminated when the load cell detected zero vertical bending force which occurs upon contact wire failure.



a) Schematic of OLE contact wire fatigue test fixture. Pivoted bearings clamping locations A and B allow bending motion while the loading lever acting at C provides tension.



b) Configuration of OLE fatigue apparatus. Note that the orientation of the contact wire is the reverse of its normal installation with its running surface upppermost.

Figure 2 Properties of OLE contact wire fatigue test fixture

2.2. Specimen Preparation

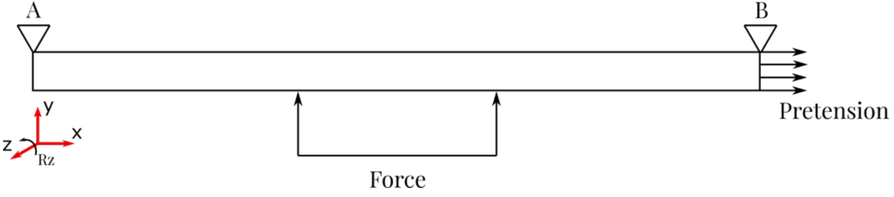
The aim of the work was to use contact wire as manufactured, potentially also with defects from operation in field conditions, and not to manufacture conventional test specimens, i.e., it was intended as a component test not a purely materials test. For the initial test series copper-silver contact wire (CuAg0.1) of 120 mm^2 cross sectional area was used (free of wear, diameter of 13.2 mm). Tensile testing of this wire showed that it had 0.2 % proof yield strength [21] just over 300 MPa and strain of 3.1×10^{-3} (poison ratio:0.3 Young's modulus 120 GPa) The proof yield strength is a derived property which is not a well-defined point on the stress-strain curve of CuAg0.1, therefore, it still produces an amount of permanent/plastic deformation. The tensile strength of the contact wire was approximately 375 MPa which was slightly higher than that required of CuAg0.1 wire by standard BS EN 50149 [22].

Minimal preparation was required in simply slicing 400mm of contact wire from the as manufactured material. Care was taken that the material was free from kinks, surface scratches or handling damage as such pre-damage was not a focus of the initial tests.

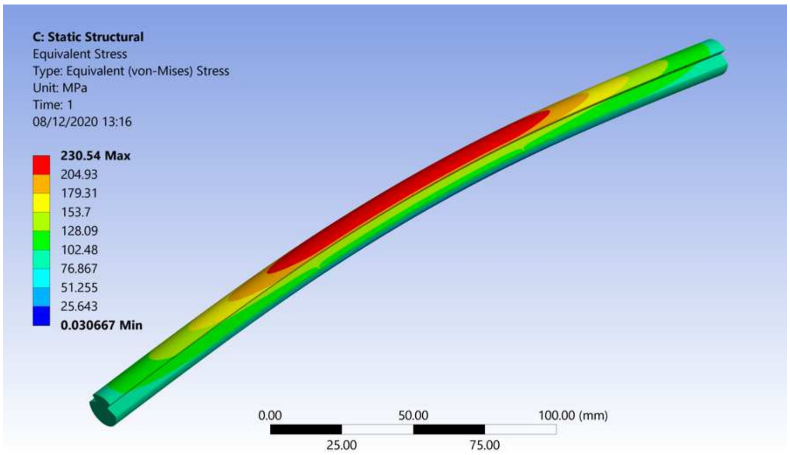
3. Fatigue testing

If wear due to contact loading against the pantograph were the primary test consideration it would be simple to apply the same contact force as measured on the full-scale real-world system. For a bending fatigue configuration at small scale this choice is not so simple and requires consideration of what the test is designed to reproduce. In service the wires deflect considerably over a long distance ahead and behind the pantograph, but this vertical translation of the wire is not of significant interest as bending local to the pantograph is the primary driver of fatigue damage. For a bending configuration the maximum surface stress and consequent strain in the wire is of much greater relevance than the contact load or bulk elastic deflection.

Considering these factors, the vertical test load was determined by a strain to vertical bending force relationship determined using a finite element (FE) model in Ansys 19.1 with the contact wire under pretension. A solid element 3D model of the contact wire was created with the standard cross-sectional geometry defined in EN 50149. In the FE model, the boundary condition of the contact wire was defined as a beam subject to tension simply supported at the points (A and B) with vertical load application (Figure 3a). A tetrahedral element (type SOLID187) was used to represent the wire, with a convergence analysis was applied to the FE model to determine the optimum number of elements and ensure element quality checks were satisfied (average of aspect Ratio, Jacobian ratio and Skewness, 1.87, 0.98 and 0.24, respectively). The convergence points in which the maximum stress became flatten and steady in the graph was selected to be the optimum element size of 9574.



a) Boundary conditions



b) Maximum deformation and stress distribution (in red contour)

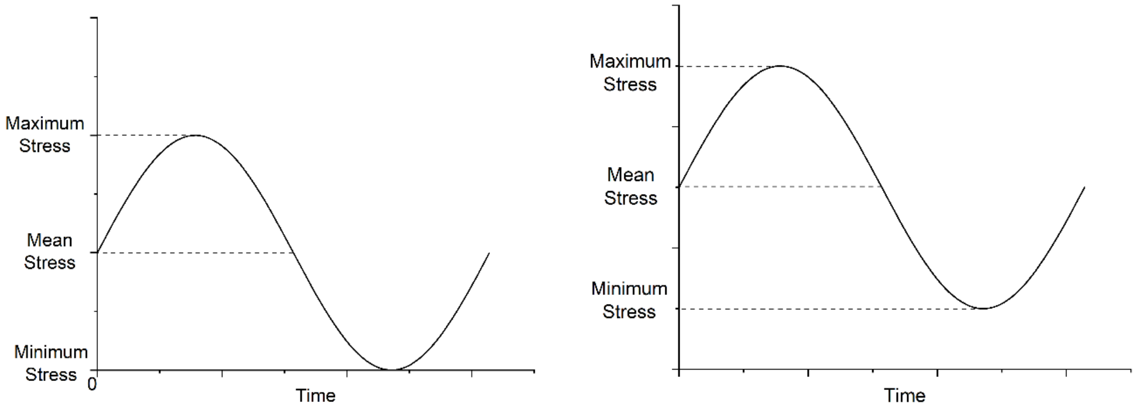
Figure 3 Boundary conditions and stress in FE model of the contact wire

Table 1 presents the results obtained from the FE analysis for loads exposing the contact wire to a wide range of potential service conditions for fatigue testing of OLE wire specimens under combined bending and tension. In the table, deflection is the vertical displacement in the centre of the contact wire relative to the end of the sample, vertical forces are the selected test loads for the experiments and total strain/stress corresponds to the stress/strain results in the centre of the contact wire at the selected vertical test loads. In order to determine test loads, equivalent pantograph force data from an existing model was used. Strain values in the real span lengths due to the pantograph contact force was used from an existing model [14] and the test loads were selected to create equivalent surface strain same as the real span length.

Table 1 Load selection for fatigue testing

Deflection mm	**Test Vertical Force N**	**Equivalent Pantograph Force in Real Scale N**	**Total Strain (mm/mm) 10^{-3}**	**Plastic Strain (mm/mm) 10^{-3}**	**Stress MPa**
2.05	1750	272	2.470	-	248
2.66	2000	334	3.027	-	280
3.96	2500	470	4.253	1.15	324
5.22	3000	615	5.553	2.45	347
6.25	3400	739	6.664	3.56	365

Looking at how an overhead line is loaded, the passing pantograph translates and bends the contact wire upwards, but it cannot pull it downward. It returns to its static position under gravity alone. Therefore, in applying load in the experiments the aim was to cycle the specimen such that its surface transitioned from line tension loading alone to maximum bending and back each period. Applying the zero-based vertical cyclic loading to a tension free wire would produce a stress cycle as shown in Figure 4 (a). When combined with contact wire tension the maximum and minimum stress are increased by the same amount (Figure 4b). This increases the mean stress and the loading ratio (ratio of maximum and minimum strain). Consequently, the entirely positive stress regime represents a much more damaging configuration than would be seen in a conventional bending test with positive and negative elements to the stress cycle. Experiments were conducted for a range of peak surface stress (by varying bending load at constant longitudinal tension) so stress ratio was varied between 0.12 and 0.32.



a) Zero based cyclic loading

b) Cycling loading with contact wire tension

Figure 4 The influence of contact wire tension on mean stress

It should be noted that the configuration of the test meant maximum positive bending and maximum stress would exist on the bottom surface of the sample, whereas for an installed wire in an open section of track the top surface would be exposed to greatest positive bending from pantograph uplift. The orientation of the wire in the test apparatus was therefore reversed with its usual running surface uppermost (Figure 3). This was simply a convenience for testing and of no consequence to the stress experienced by the sample. To avoid confusion in the results and discussion below ‘top’ and ‘bottom’ of the wire refer to service installation orientation not the position while under test.

4. Results and Discussion

4.1. Fatigue life

Table 2 shows the fatigue life cycles to failure obtained from the experiments. Results were correlated with the total surface strain from tension and bending. To assess consistency of results and identify outliers the tests were conducted to achieve a maximum fatigue life deviation between tests of ten per cent at any loading condition. Where larger deviations existed, tests were repeated.

Table 2 Fatigue test results

Test Number	**Loading Ratio (R)**	**Min Strain (tension alone) [x10^{-3}]**	**Max Strain* (combined tension and bending) [x10^{-3}]**	**Fatigue life (N_f)**	**Deviation◆**
1	0.32	0.79	2.470	6588432	-
2				7010955	6.4 %
3	0.26	0.79	3.027	1650211	-
4				1424516	13.6 %
5				1286928	9.6 %
6	0.19	0.79	4.253	480655	-
7				410951	14.5 %
8				427888	4.1 %
9	0.14	0.79	5.553	210896	-
10				228444	8.3 %
11	0.12	0.79	6.664	70708	-
12				73528	3.9 %

* Theoretical plastic strain can be taken to start after strain of 3.1x10^{-3} is reached at 0.2% proof stress

◆ Baseline value for calculating deviation in results for each loading condition shown as ‘–’.

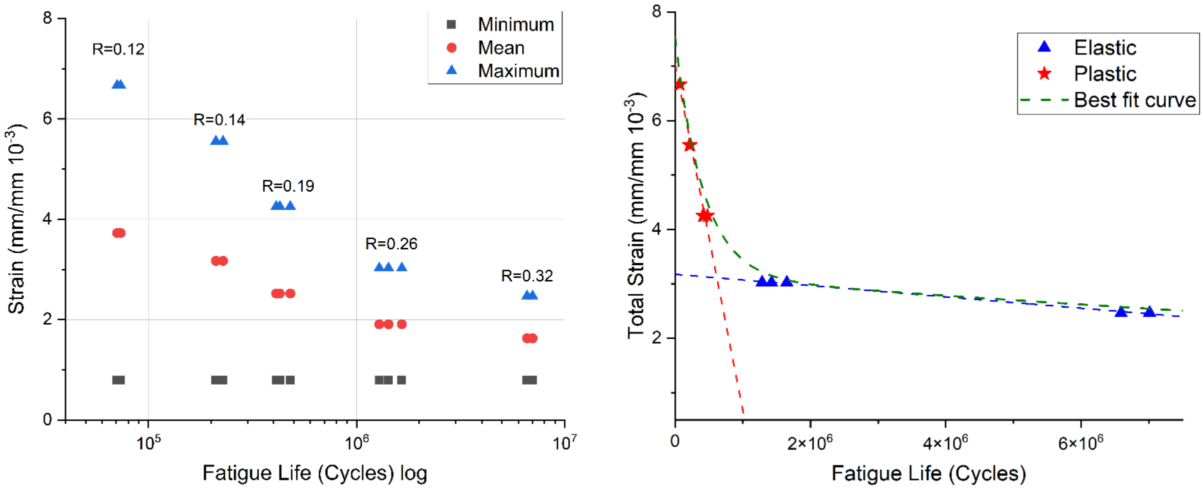
4.2. Strain-life Interpretation

Test results are plotted on a strain-life graph in Figure 5a with minimum, maximum and mean strain values (note the log scale for fatigue life to better separate the cases). Unlike for ferrous metals it was not expected to identify a fatigue limit for the copper-based contact wire alloy as this is not a characteristic of the material. However, as would be expected the fatigue life of the contact wire became shorter when the maximum strain was increased. The minimum strain level in each test is uniform so there is no correlation of this with the fatigue life. Similarly, the mean strain changes only as a consequence of changes in the maximum strain and it is the maximum that is the controlling parameter.

The fatigue life curve of the contact wire with total strain was plotted in Figure 5b using a linear fatigue life axis. Points are separated into cases with only elastic deformation and those including also plastic deformation. Cases with plastic deformation (representing severe loading such as may be found at points of very poor OLE dynamics) resulted the contact wire fatigue lives below 500k cycles. However, loading ratios above 0.19 showed fully elastic loading characteristics with greatly extended lives. According to the best fit fatigue life curve, copper-silver contact wire fatigue life can be represented by equation (1)

$$N_f = 2.169\ 10^{11}\ \exp(-4.288\ \varepsilon) + 6.363.10^{6}\ \exp(\ -0.6269\ .\varepsilon) \qquad \text{Eq. 1}$$

where N_f is cycles to failure and ε is maximum strain (combined tension and bending). The curve for the total strain against cycle to failure showed a typical strain-life characteristic with a tendency towards a very shallow gradient when the elastic strain predominated.



a) Strain-life results of tested contact wire samples

b) Maximum total strain (sum of elastic and plastic components) vs fatigue life of the contact wire

Figure 5 Fatigue life results of OLE contact wire samples

4.3. Stress-life interpretation

Although the strain-life interpretation is useful stress parameters can also produce insight, offering the results in a potentially more accessible format easier to relate the outcomes to controllable parameters of the OLE such as the line tension. The parameter developed by Smith [23] provides a single “equivalent stress” [11], [24] value which includes mean stress (σ_m), stress amplitude (σ_a), strain amplitude (ε_a) and Young’s modulus (E), and expressed as follows.

$$\sigma_{eq} = \sqrt{(\sigma_m + \sigma_a)\varepsilon_a E} \qquad \text{Eq. 2}$$

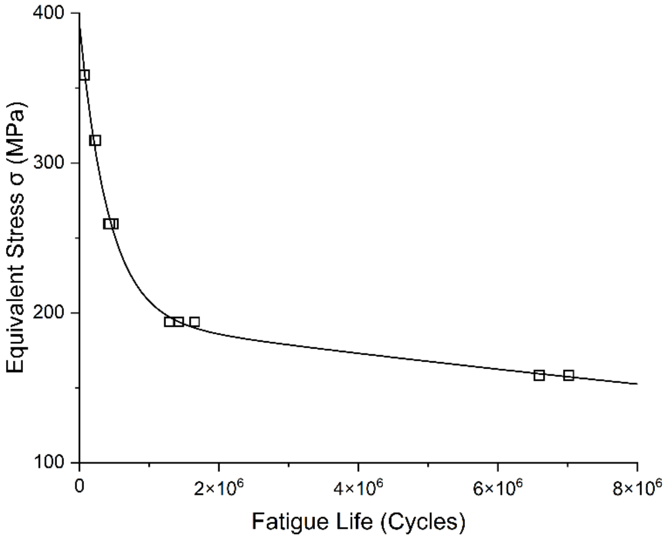


Figure 6 The relation between equivalent stress and fatigue life cycles

The conditions used in the experiments were converted into equivalent stress with Eq. (2) and plotted with fatigue life in Figure 6. A second-order exponential curve fitting was applied to the data points in this SN format producing Eq (3).

$$N_f = 1.468.10^{12}\ \exp\left(-0.0799\ \sigma_{eq}\right) + 2.139.10^{7}\ \exp\left(-0.01495\ .\sigma_{eq}\right) \qquad \text{Eq. 3}$$

4.4. Fracture surfaces

Fracture surface inspection was conducted after the fatigue failure of the contact wire samples. It was seen that all of the samples showed similar fracture behaviours with a crack initiated at the most highly stressed tensile region (that would be the top surface when installed) and final failure with plastic flow evident in the last ligament towards the bottom.

Figure 7 shows the surface and direction of the fracture in the contact wire sample. A degree of necking was observed prior to final failure of the contact wire when the crack had extended far enough that the remaining ligament of material was taken above yield by the combination of axial and bending stress.

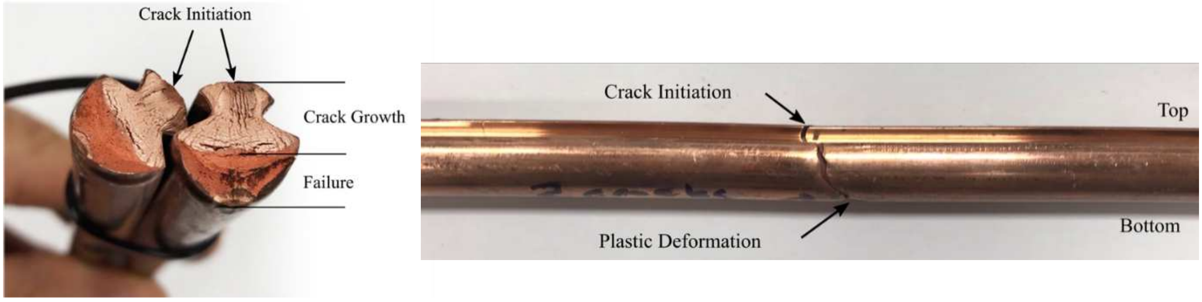


Figure 7 Fracture surface and stages in the contact wire after fatigue testing

4.5. Choice of test duration

When contact wire is installed in service every pantograph passage corresponds to a single high amplitude stress cycle, typically preceded and followed by a large number of low amplitude oscillations in the wire [25]. Considering the high stress cycle to be the controlling event we can estimate correlation between the fatigue life observed in the laboratory and the number of trains passing before failure would occur in service. Maximum life observed in the tests (for purely elastic conditions), *Table 2*, is in the order of 7 million cycles. Considering high-speed mainlines experiencing heavy traffic, passage of around 150,000 pantographs per year may occur [19], indicating that the life of 7 million cycles would be equivalent to over 45 years of traffic. Wear life of wires is typically 30-50 years indicating that the range of conditions explored spans those in which life is likely to be limited by wear through to cases where the predicted fatigue life would represent less than a year of traffic. Although this short fatigue life is considered an extreme condition with very rapid failure, it is still a representative test condition [18].

5. Conclusions

Sudden release of tension in railway overhead line systems due to contact wire fatigue failure is a dangerous and disruptive event. While conventionally limited by wear the life of OLE wire on high-speed lines can also be determined by fatigue, but the ability to understand the process of crack initiation and growth at a component level has been lacking. This study demonstrates the potential of a new test configuration for assessing fatigue life of overhead contact wires and shows results of tests covering a range of fatigue lives. The results indicated how a low number of high strain events (even when not drastically above intended working conditions) can lead to failure well before the intended wear life.

The use of a short (400mm) specimen cut from parent overhead line wire ensures the test is simple to conduct and is equally suited to investigation of new or pre-worn wires. Use of a four-point bending arrangement has a particular benefit for component as opposed to material testing. Overhead lines are susceptible to surface damage during installation, during use, or due to electric arc exposure when pantograph dynamics are poor. Such conditions may occur due to contamination of the line with ice, or at imperfect overhead wire geometry in transitions through bridges, tunnels and junctions. Loaded in a three-point bending configuration would make alignment of any pre-existing defect with this load point a controlling factor in the fatigue test outcome. In contrast, the four-point configuration used here places a length of wire under uniform stress making it more realistic for exploring the effect of pre-damage. Such an investigation would not be possible with conventional standard fatigue samples that focus on the material behaviour alone. An important application of the technique will be in developing understanding of wire damage and the possible return on the investment needed to prevent it.

Acknowledgement

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