AGED ACSR CONDUCTORS
PART II - PREDICTION OF REMAINING LIFE

by

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Abstract - The companion paper, "Aged ACSR Conductors Part I - Testing Procedures", describes methods of test to determine the overall condition of Ontario Hydro's overhead conductors. This paper presents the analysis of the test results relative to estimated "end-of-life" values. The remaining useful life of conductors can be estimated from the curves of progressive degradation. Air pollution studies have led to an environmental corrosion index, which has been correlated with remaining life based on the torsional ductility of steel core wires. This has been used to map expected conductor life across the province. The average service life is found to vary between about 67 and 77 years depending on the local contamination level.

Key words: ACSR conductor, aging, corrosion, refurbishment, overhead line, testing

INTRODUCTION

The definition phase of Ontario Hydro's overhead line refurbishment study, included tests of samples of all components, from the foundations, through towers, insulators and hardware, to the conductors and overhead ground wires. Some of these tests have been reported elsewhere in the literature[1,2,3]. Overhead ground wire replacement was under good control within a systematic program of testing and replacement. All other components of the line were generally in good condition. Where there has been some local degradation, parts could be replaced or even upgraded, as part of normal maintenance procedures. Thus the need to refurbish was strongly guided by the condition of the conductor. This and the companion paper, "Aged ACSR Conductors Part I - Testing Procedures", focus on the conductor tests and their interpretation.

The conductors used on Ontario Hydro's lines built before 1950 are mainly aluminum stranded with a galvanized steel core (ACSR). Samples of the few remaining copper conductors brought to the laboratory for tensile strength and torsional ductility tests were found to be virtually as new. On the other hand the old ACSR conductors show great variability in condition, attributed to differences in exposure to corrosive agents, particularly to industrial effluent. There is little evidence of reduced conductor life due to vibration induced fatigue. This is due to use of low tensions and suitable vibration dampers. There is also a program of gathering existing records of air quality and of monitoring changes. The records indicate a progressive increase in environmental acidity over the lives of these lines. Younger conductors are expected to have shorter lives than the samples discussed in this paper due to the increasing atmospheric corrosivity.

As described in detail in the companion paper, 77 conductors were tested in situ for loss of galvanizing using an eddy current based device invented by CEGB staff[4]. Due to difficulties in obtaining outages, the device was modified to permit its use on live lines. Also, 41 samples of conductor were cut out of representative lines at various locations in the spans. The conductor constructions included: 6/1 (12%); 54/7 (7%); 30/7 (44%); 26/7 (17%); 12/7 (2%); 6/7 (15%); and 54/7 (2%). The tensile strength and torsional ductility of individual aluminum and steel strands were determined from laboratory tests. The aluminum layers were found to have retained their original properties to a large degree. On the other hand the steel strands showed reductions in both tensile strength and the number of turns to failure.

A data base of these conductor data and related information, such as the weather conditions and atmospheric chemistry data, has been established in support of the continuing refurbishment activity. It is anticipated that there will be a continuing need for up-to-date information on line and particularly conductor condition, and of the changing factors influencing remaining life. This will be needed to provide data for the continuing prioritization of lines for refurbishment within a manageable program.

DATA BASE FOR TRANSMISSION LINE REFURBISHMENT

Evaluating the longevity of Ontario Hydro's older transmission lines requires large amounts of data on various aspects of transmission lines. The importance of establishing a transmission line data base, containing relevant information and accessible to all interested parties, was understood from the early stages of the refurbishment project.

The transmission line refurbishment data base was derived from two data bases already in existence at Ontario Hydro. One data base, containing circuit data for approximately 800 line sections, was modified to include a summary of the results of tests of conductor corrosion and mechanical condition. The other data base, containing information on about 6300 structures in Ontario Hydro's transmission line network, was modified to include summary information from tests of soil conditions, foundation corrosion, anode condition and conductor damage. The circuit data base was used for the conductor longevity studies discussed in this paper. When available, the following information can be stored in the circuit data base:

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region
line section
length
structure type
in service date
tenant circuit
circuit number
section name
structure numbers
voltage
property number
line orientation

conductor type
conductor age
damper type and history
rated strength
skywire type

corrosion test rating
length inspected
date of test
steel ductility

torsional ductility
source structure
aluminum condition
tensile strength
zinc condition
overall condition

A menu driven system was developed to provide easy access to the above data bases and to produce custom designed reports on: circuit details by region; line details; environmental test data; soil test data; foundation test data; anode test data; tower corrosion test data; conductor test summary; and conductor test detail. The data base will eventually be interfaced with Ontario Hydro's digital mapping system. This will provide a number of advanced features. For example, transmission lines can be superimposed any on the Ontario map, color coded to date of installation, system voltage or local atmospheric conditions.

END OF LIFE CRITERIA

To determine the remaining useful life of any tested conductor, an unacceptable deterioration level has to be established for each diagnostic procedure. The steel core corrosion detector measurements indicate the average thickness of zinc remaining. Due to variations in zinc thickness and uncertainty regarding original thickness, the indication is qualitative. A relatively coarse scale of one to four was used to categorize the samples. The instrument does not respond to effects that take place within the steel wires after the zinc coating is pierced or removed, such as surface rusting, pitting of the surface, or severe corrosion within the wires. Consequently the only end point that can be used for these measurements is the maximum value of four which corresponds to 80 to 100 percent loss of zinc. Several more years of life remain in the conductor when this value is first reached, but from a single measurement it is not possible to differentiate between samples that have just reached this value and those that have seriously corroded cores.

Tensile tests on conductor samples give more precise measurements which can be directly related to static conductor overloads due to heavy icing or high winds. New conductor samples show an average strength of 112% of rated tensile strength (RTS). An assessment of loadings on a number of older lines has shown that most conductors reduced in strength to 80 percent of RTS would still support a 50 year return loading of heavy ice plus wind, and in some cases even lower strengths would be sufficient. In addition to static loads, dynamic effects, primarily due to galloping, generate additional high loads, which may be superimposed on high static loads and the total can be more critical. Because of their infrequency, and the difficulty in determining their magnitude, these dynamic loads were not included in the analysis of the required tensile strength.

Data from individual wires show that the reduction in strength was almost solely in the steel wires. Final conductor failures are usually complex processes in which a partially deteriorated conductor suffers some propagation of fatigue cracks, possibly initiated at corrosion pits. Final breakage may be from a quasi-static weather induced loading such as icing, or a dynamic loading such as galloping. Static loading data and tensile strength data do offer an approach to estimating remaining life based on the local weather records. The return period of the weather conditions that would produce load levels sufficient to cause the tensile strength to be reached can be determined. This is a guide for the remaining life and for the relative condition of various lines for prioritization in the refurbishment program.

The torsional ductility tests of a wire from an old conductor are a measure of the cracks within the microstructure. As the conductor ages, the number of turns to failure reduces from about 35 in a new wire to zero. An analysis of the fatigue process has been carried out which is summarized in the appendix. This relates torsional ductility to fatigue strength. The damage due to the cyclic loading generated in one representative galloping event can be estimated and the number of such events that the conductor can withstand is derived from the fatigue curve using Miner's law. Weather records then indicate the number of galloping incidents, and the remaining life in years can be estimated. While this analysis is recognized as an indication only, it has been compared with laboratory fatigue tests of old conductors. This has led to an end of life criterion of five turns. The use of galloping data in this analysis may include some conservatism, but this is offset by the sampling procedure which may not necessarily include samples from the most corroded line sections.

CONDUCTOR LIFE ESTIMATES

Measurements of conductor condition by the three testing procedures have been related to age and location in the province and to the end of life criteria described above. This section presents the results of those analyses and the estimates of conductor life that was one of the factors subsequently used in prioritizing lines for refurbishment. It should be noted that these life estimates require data on the initial unaged condition of the conductors. New samples of similar size and construction were tested by each method. However these samples were from present day manufacturing practice and differences in factors such as: dimensional tolerances, steel composition, zinc thickness and uniformity, may not be properly represented. For some lines more than one measurement was taken of the conductor condition. The values for the most degraded section were used in the analysis because failure of any section of the line constitutes failure of the whole line.

Life Estimate Based on Zinc Loss

Sections of conductor on seventy seven lines were inspected using the corrosion detector and given a rating of one to four. The lines tested are from industrial, residential, agricultural and undeveloped parts of the province, and ranged in age from 16 to 79 years. Short samples of new conductors of similar construction were used to establish the rating of one, or "as new" setting of the equipment. Figure 1 shows the corrosion detector ratings plotted against age for all samples. The maximum rating of four corresponds to zinc loss of 80 percent or greater, and is the worst condition that can be detected. The figure includes curves indicating the main trend, and the 10, 30, 70 and 90 percentiles of the data. With Y representing the corrosion detector rating and X the age of the sample in years, the mean line is given by:

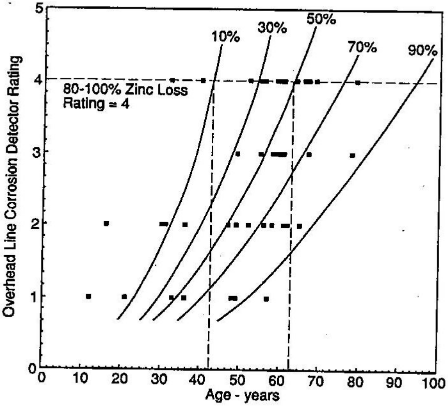


Fig. 1. Overhead line corrosion detector rating vs. age for 77 conductor samples.

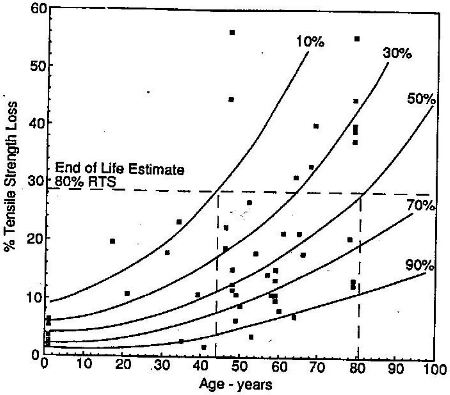


Fig. 2. Tensile strength loss vs. age for 50 conductor samples. Initial strength = 112% RTS.

$$Y = 0.00049X^{2.17}$$

The average age when a sample reaches the terminal value of four is 63 years, and the lower decile age is 43 years. This spread is mainly an indication of local variations in corrosion severity, but also includes differences between conductors in their "as new" condition. Assuming that the relative rate of degradation is constant over time, these curves can also be used to estimate when a sample is expected to reach this end of life rating.

Life Estimate Based on Tension Tests

Samples of conductor were removed from 44 lines across the province and the individual wires were tested in tension. The strength, as a percent of rated tensile strength (RTS), is plotted against age for each sample and for 6 new conductors, in Figure 2. The figure includes a line representing the end of life estimate at 80 percent RTS. The mean and 10, 30, 70, and 90 percentile curves have been fitted to the data. The mean curve is described by:

$$Y = e^{1.41 + 0.024X}$$

where Y represents the strength loss in percent of initial strength, and X the age in years. From tests on new samples the initial strength is estimated to average 112 percent of RTS. The average life to the end of life estimate based on tension tests is 81 years and the lower decile 44 years. The remaining life can be estimated for each sample based on the curves in the figure.

Life Estimate Based on Torsional Ductility Tests

Torsional ductility tests were conducted on steel wires from 41 conductor samples removed from old lines and on 5 new conductors. The average number of turns to failure of the outer layer of steel wires in the core, is plotted against age, in Figure 3. The figure includes the end of useful life estimate of 5 turns, which is derived from an analysis of conductor fatigue due to galloping motions, summarized in the appendix. Curves have been fitted to the data to represent the 10, 30, 50, 70 and 90 percentiles of the data. The average life to reach the end point defined by this test method is found to be 70 years, with the lower decile being 39 years. These results show the most dispersion, some of which may due to variations in the thickness of the zinc coatings of the samples of new conductors used to calibrate the device. This test does appear to be a very sensitive indicator of variations in local conditions. The mean fitted curve is given by:

$$Y = 40 - e^{1.65 + 0.027X}$$

As for the tests of zinc loss from the steel core and tensile strength, the plotted curves can be used to estimate remaining life for each sample tested.

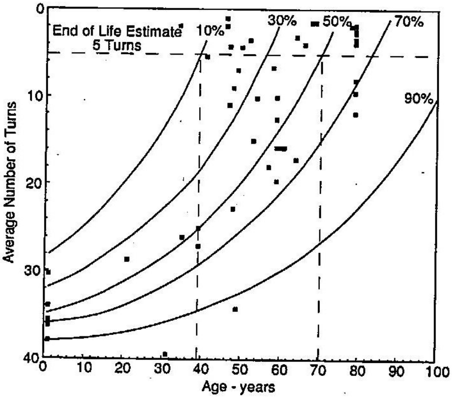


Fig. 3. Torsional ductility of outer layers of steel core vs. age for 46 conductor samples.

Conductor Life Variation by Regions

The conductor samples were taken from all over the province, which is divided into five geographic regions. The Central, Georgian Bay, and Western Regions contain the most industrial and commercial developments, while the Northeastern and Northwestern Regions are largely undeveloped land. Eastern Region contains some farm land, but little industry. Figure 4 shows the mean conductor life, and the 90 percent confidence bounds, determined by the three test methods, for each region. The overall average of the three tests is also included in the figure. The data show that in every region the corrosion detector indicates the shortest average life, with the torsional ductility and tensile tests following in order. There is a consistent geographic pattern of relative life spans, with the shortest overall average lives in the Central and Western Regions (67 and 72 years), and longer lives in the Eastern, and combined Northeastern and Northwestern Regions (77 and 76 years) This consistency suggests that these tests are measures of related degradation mechanisms. From the average values the corrosion detector indicates end of life at 66 years, the torsional ductility tests at 71 years, and the tensile tests at 81 years. These results support the use of the corrosion detector as a preliminary diagnostic tool, with the mechanical tests providing more precise indications of end of life.

Conductor Life Variation by Number of Core Layers

The data have also been grouped according to the number of layers in the conductor core. Figure 5 shows the results of this breakdown. The conductors with single layer cores have shorter lives that two layer core conductors by all test methods. The predicted average lives are 63 years for single layer and 75 years for two layer cored conductors.

ENVIRONMENTAL CONSIDERATIONS

The environmental factors influencing the corrosion of transmission line conductors were investigated and an attempt was made to derive a corrosion index which could be used to predict the expected lifetime of conductors in various parts of the province.

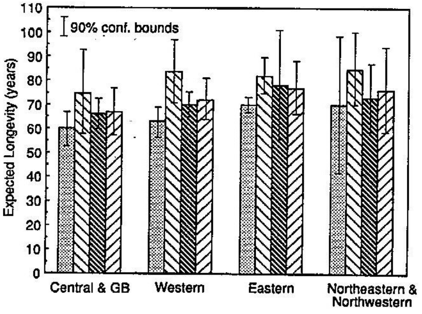
Corrosive Chemical Species and Their Distribution in Ontario

Samples of conductors from three locations representing a gradient in atmospheric pollution were analyzed to establish the degree of deterioration and the chemical nature of deposits and corrosion products. A test procedure involving x-ray diffraction and various spectroscopic techniques was used. The chemical nature of the corrosion products indicates that corrosion is most severe in acidic, sulphate-chloride environments. Corrosion mechanisms consistent with this observation are as follows. Corrosion of galvanized steel occurs by dissolution and precipitation of zinc, in acidic media, such that corrosion products accumulate on the surface aqueous layer. Corrosion of aluminum involves breakdown of the passivating aluminum oxide layer by adsorption of anions, chemical reaction and dissolution, and then direct attack of metal.

The geographical distribution of air pollutant concentrations, precipitation acidity and composition, and meteorological conditions was determined using data routinely collected by environmental and meteorological agencies in Canada. The data analysis was performed using a graphics package developed by the National Centre for Atmospheric Research. The task of plotting contours of irregularly distributed data was performed using a utility which "triangulates" data and then imposes a dense, "virtual" grid, in which each point is assigned a value interpolated from neighbouring data points. The method is reasonably accurate for slowly varying fields or dense monitoring networks. An example of the distributions derived using this method is shown in Figure 6.

Atmospheric Corrosion Index

Rates of conductor deterioration, in terms of average yearly changes in tensile strength, torsional ductility and overhead line corrosion detector ratings, determined experimentally as described elsewhere in this paper, were correlated with pollutant and meteorological factors. This analysis indicated that the following factors should be considered in the derivation of an atmospheric corrosion index for Ontario: SO_4^{2-}, Cl^-, NH_4^+ in precipitation; Ca in suspended particles; SO_2 in air; and, total amount of precipitation.



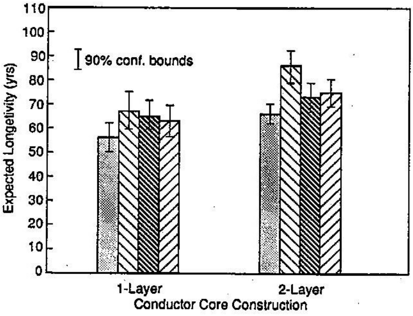


Fig. 4. Regional averages of estimated conductor longevity based on three test methods.

Fig. 5. Average longevity of conductors with single and two-layer steel cores based on three test methods.

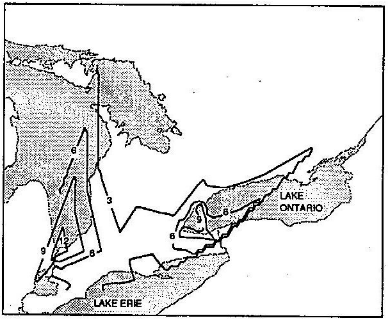


Fig. 6. Average SO_2 concentration in air in Ontario.

An atmospheric corrosion index, which measures the corrosivity of the local environment, was developed based on the above factors. The algorithm arrives at an index rating by comparing successively key environmental parameters with threshold values, see Figure 8. The useful conductor life, which corresponds to each rating (1 to 5) has been determined by correlation to average yearly loss in torsional ductility. This is shown in Figure 9. The index shows great promise as a predictor of ductility loss and expected lifetime of conductors.

The geographical distribution of the atmospheric corrosion index is shown in Figure 10. Two "hot spots" are seen, one in Southwestern Ontario due to pollution sources in the U.S.A. and another associated with the Greater Toronto urban area. The index drops sharply toward the north.

It is possible to estimate the lifetime of conductors exposed to current environmental conditions across Ontario. To do this, the correlation equation derived from the data shown in Figure 9, ie,

$$y = 0.10x + 0.27$$

where y is the average yearly loss in ductility and x is the atmospheric corrosion index rating, can be used. If a low torsional ductility is taken as a measure of useful life then the distribution of conductor lifetimes, such as shown in Figure 11 for a ductility of 5 turns, is obtained. The uncertainty in these estimates is 5-10 years.

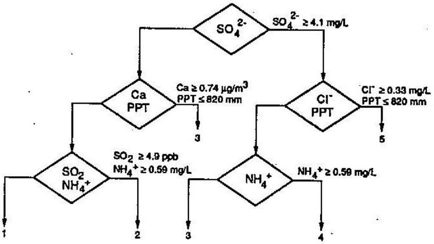


Fig. 8. Environmental corrosion index algorithm.

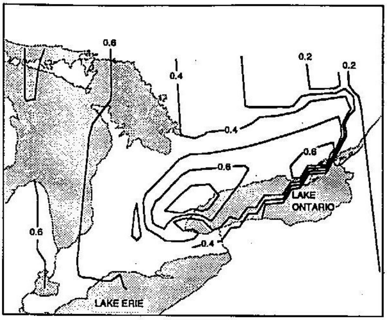


Fig. 7. Average annual loss of torsional ductility in Ontario in turns/year.

CONCLUSIONS

1) The studies of the pre-1950 ACSR conductors have confirmed that the galvanized steel core wires are corroding.

2) Measurements of galvanizing loss using a corrosion detector provide advance warning of severe loss of mechanical properties.

3) Torsional ductility tests of samples cut from conductors provide a more sensitive indicator of remaining useful life.

4) A program of corrosion monitoring plus torsional ductility testing of conductors can indicate their present condition, permit full use of their remaining life, and minimize the risk of premature failure.

5) Due to increasing levels of atmospheric corrosion, newer conductors are not expected to last as long as those tested in this program.

6) The longest lives are found in the Northeastern and Northwestern

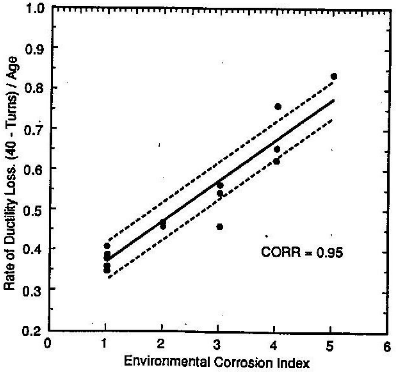


Fig. 9. Average annual loss of torsional ductility vs. environmental corrosion index.

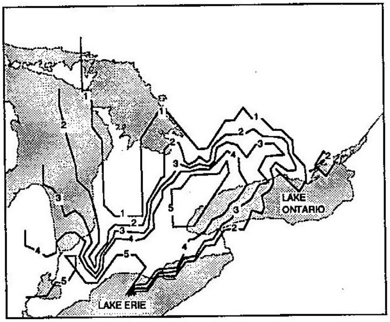


Fig. 10. Environmental corrosion index distribution for Ontario.

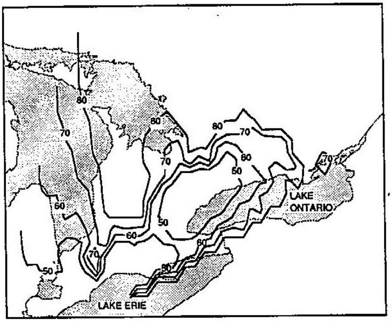


Fig. 11. Predicted conductor life distribution for Ontario.

Regions, with shorter lives, in order, in the Eastern, Western and Central Regions.

7) For planning purposes a mean useful life of 70 years is considered valid for existing conductors.

8) Existing conductors with single layer steel cores last about 12 years less that those with two layers.

RECOMMENDATIONS

1) Continue field monitoring and laboratory testing of conductors and maintenance of the data base.

2) Extend the atmospheric pollution surveys to a finer grid, particularly near sources of industrial effluent.

3) Investigate methods for improving corrosion protection on new conductors.

ACKNOWLEDGEMENTS

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APPENDIX

Torsional Ductility and Fatigue Strength of Steel Wires

In torsional ductility tests wire specimens are held under a slight tension between chuck jaws and twisted to failure. The active length of the specimens is 120 times the wire diameter. One full twist applies a shear strain of 2.62 percent. A new specimen would undergo about 35 turns to failure which is a shear strain of 92 percent. This is comparable to the strain to failure of a mild steel specimen in tension which is about 90 percent[9]. The fatigue strength of steel, in terms of total strain amplitude, e_{tn}, versus cycles to failure, n_f, can be estimated from the strain to failure, e_{to}, determined from a single tension, or torsion, test. The total strain, e_t, can be separated into the elastic and plastic components, e_e and e_p, which in turn are related to the stress, s, the elastic modulus, E, and constant, K, and logarithmic exponent, n, derived from the stable cyclic stress-strain curve.

$$e_t = e_e + e_p = \frac{s}{E} + Ks^n$$

The fatigue curve can be derived from the two strain components using the Coffin-Manson[10,11] and Basquin[12] power law relationships.

$$e_{tn} = e_{en} + e_{pn} = An_f^b + Bn_f^c$$

After some manipulation the fatigue curve can be expressed in terms of the strain, e_{to}, in a tension or torsion test as:

$$e_{tn} = e_{to}(4n_f)^c + Ce_{to}{}^{1/n}(4n_f)^b$$

Based on an available data base from fatigue tests on normalized mild steel specimens[9], the four constants, C, n, b and c have values of 180.2, 3.23, -0.14, and -0.52 respectively. These curves are plotted in Figure 7 for initial strain values of 92, 26 and 13 percent, corresponding to torsional ductility values of 35, 10 and 5 turns respectively. Samples from a conductor installed on a line in 1911 were tested in fatigue and torsional ductility and these measurements are included in the figure. The average number of turns for the outer layer of wires in the core in the ductility test was 2. The corresponding strain value, 5 percent, is plotted at a life of 1/4 cycle. The result of one fatigue test, in which the strain varied between 0.020 and 0.032 percent, and failure occurred at about four million cycles, is also plotted. These points illustrate the accuracy of fit of the above analytical prediction to the fatigue curve for an aged conductor. The fit is considered acceptable considering that the source data are from polished specimens. As conducting fatigue tests on conductors is difficult and costly, this method of predicting fatigue response from simple ductility tests seems justified.

To determine the conductor life remaining in years, dynamic loadings at a suspension clamp due to a spectrum of galloping events, have been calculated. Data available from 42 observations of conductor galloping from field trials[13] of control devices, give a distribution of ratios ,k , of amplitudes in terms of the sag of the conductor. The strain at the clamp, e_c, has been derived for each amplitude for a typical span of length L and the conductor construction tested, using the Poffenberger-Swart equation[14]. The strain is given by:

$$e_c = \frac{\pi kdmgL}{32\sqrt{TEI}}$$

where; d is the wire diameter, m is the mass of conductor per metre, g is the gravitational constant, T is the tension, and EI is the effective stiffness of the conductor section.

The cyclic strains and the number of cycles at each amplitude in a four hour galloping event, are then as shown in the figure. The number of such events that will cause fatigue failure is then determined using Miner's Rule[16]. The damage at each strain level, is assumed to be proportional to the ratio of the number of cycles imposed to the number of cycles to failure at each strain level. When the damage from all strain levels amounts to unity fatigue failure will occur. For the three examples shown in the figure, with ductility values of 5, 10 and 35 turns, the fatigue lives are estimated to be 14, 56 and 691 hours of galloping, respectively. These times should be taken as guidelines only. There is more confidence in the accuracy of the ratio between lives of 1:4:49. Based on this study, a threshold ductility level of five turns appears to be a reasonable guideline for conductor replacement.

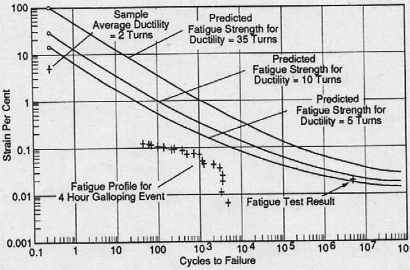

Fig. 12. Fatigue curves for steel based on torsional ductility tests and strain history from a composite galloping event.

Biographies

Biographies for D.G. Havard, D.J. Horrocks, J.Motlis and K.S. Yoshiki-Gravelsins are included in the companion paper.

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