MECSOL 2019 - Proceedings of the 7th International Symposium on Solid Mechanics
V. Tita, A. Ferreira, M.L. Ribeiro, A. Vieira and A.T. Beck (Editors), ABCM, Sao Carlos, SP, Brazil, April 15th to 17th, 2019

Fatigue Life Prediction of AA1350-H19 Wire under High Stress Gradient

I. M. Matos, P. H. C. Rocha, J. A. Araújo, F. C. Castro

Department of Mechanical Engineering, University of Brasilia, 70910-900 Brasilia, DF, Brazil

Abstract: Fatigue life prediction of AA1350-H19 wires of ACSR Tern overhead conductor was investigated. Fatigue test data of plain wires, circumferentially V-notched wires, and wires with transverse hole were obtained for fully reversed axial loading. A three-dimensional fatigue life prediction methodology—based on averaging the stress distribution in a damage zone—was implemented in the commercial finite element-based package Abaqus. The test data from the plain and the V-notched wires were used to calibrate the methodology. Fatigue life estimates of the wires with transverse hole were within factor-of-four boundaries. The results suggest that the fatigue life prediction methodology can be applied to predict the fatigue life of two contacting wires of an overhead conductor.
Keywords: overhead conductor, 1350 aluminum alloy, crack initiation, life prediction, stress gradient

INTRODUCTION

Fatigue failure of wires is the most common type of damage encountered in overhead conductors, especially in regions where the conductor's movement is restrained, such as suspension clamps, spacers, spacer dampers or Stockbridge dampers. Over the past decades, efforts have been made to understand the complex mechanical behavior of overhead conductors. However, limited work has been done on the incorporation of modern fatigue analysis tools in the life prediction of overhead conductors.

The contact of two wires of an overhead conductor usually results in severe stress concentration and high stress gradient. Since a similar feature is encountered in sharp notches, it is worthwhile to try to apply the so-called notch analogy to predict the fatigue life of two contacting wires. This work investigates the application of a fatigue life prediction methodology—based on averaging the stress distribution in a damage zone—to the life prediction of AA1350-H19 wires.

EXPERIMENTAL WORK

The material investigated in this study is the 1350-H19 aluminum alloy used to manufacture the 3.38 mm-diameter wires of the ACSR Tern overhead conductor. This alloy has typical Young's modulus $E = 69$ GPa, yield stress $\sigma_y = 165$ MPa and ultimate tensile strength $\sigma_{ut} = 185$ MPa (Kaufman, 2000). Figure 1 shows the specimens used for fatigue tests: plain wire, circumferentially V-notched wire, and wire with transverse hole.

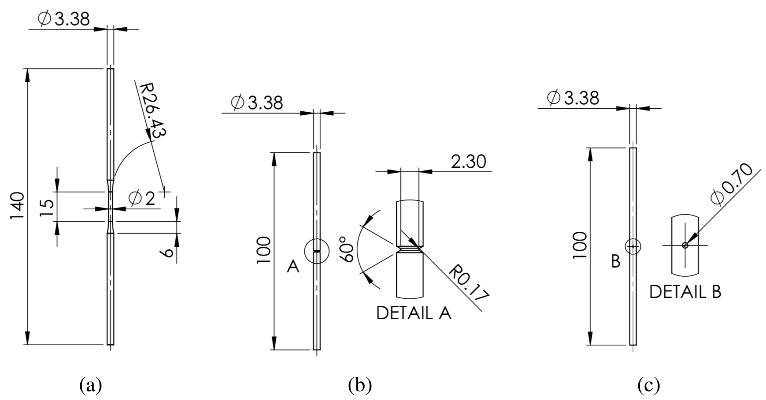


Figure 1 – Specimens used in the fatigue tests: (a) plain wire, (b) V-notched wire, and (c) wire with transverse hole.

Fatigue tests were performed using a servo-hydraulic axial testing machine (MTS Landmark) equipped with a load cell with a capacity of $\pm$ 5 kN. The specimens were subjected to fully reversed axial loading. Failure was defined as the complete rupture of the specimen, and run out as 5×10^6 cycles. Fatigue test data of all the specimens are summarized in Tables 1 to 3, where D is the specimen diameter, $d_{\min}$ is the minimum specimen diameter, d_h is the diameter of the transverse hole, r is the V-notch radius, α is the V-notch opening angle, $\Delta F/2$ is the axial load amplitude, $\Delta S/2$ is the nominal stress amplitude in the net cross-sectional area and N_f is the number of cycles to failure. The nominal stress amplitude–fatigue life diagram of each data set is shown in Fig. 2, where horizontal arrows represent run out tests.

Table 1 – Fatigue test data of plain wires.

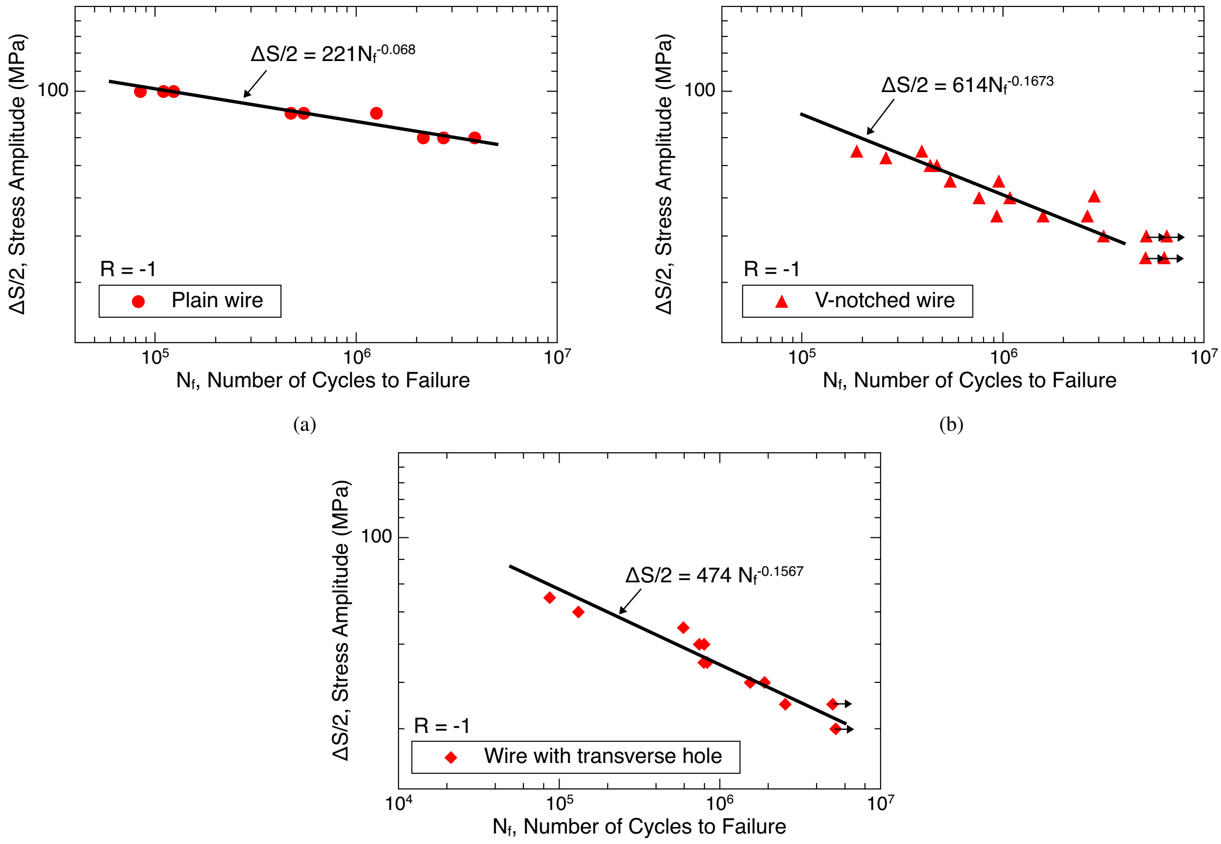
Specimen ID	D [mm]	d_{min} [mm]	$\Delta F/2$ [N]	$\Delta S/2$ [MPa]	N_f [cycles]
1350U1	3.38	2.00	314	100	84,356
1350U2	3.38	2.00	314	100	109,834
1350U3	3.38	2.00	314	100	123,242
1350U4	3.38	2.00	283	90	473,045
1350U5	3.38	2.00	283	90	547,421
1350U6	3.38	2.00	283	90	1,257,270
1350U7	3.38	2.00	251	80	2,150,257
1350U8	3.38	2.00	251	80	2,713,742
1350U9	3.38	2.00	251	80	3,876,713

Table 2 – Fatigue test data of circumferentially V-notched wires.

Specimen ID	D [mm]	d_{min} [mm]	r [mm]	α [^{o}]	$\Delta F/2$ [N]	$\Delta S/2$ [MPa]	N_f [cycles]
1350N17	3.45	2.42	0.17	61	346	75.0	187,247
1350N15	3.44	2.55	0.18	64	372	72.7	261,607
1350N11	3.40	2.44	0.18	60	352	75.0	394,000
1350N30	3.42	2.37	0.17	61	308	70.0	433,502
1350N1	3.41	2.41	0.15	62	319	70.0	467,836
1350N28	3.44	2.39	0.17	60	292	65.0	545,728
1350N19	3.43	2.57	0.17	63	311	60.0	758,576
1350N27	3.43	2.38	0.17	60	245	55.0	929,024
1350N24	3.38	2.31	0.17	62	272	65.0	953,328
1350N16	3.45	2.58	0.17	63	314	60.0	1,080,320
1350N20	3.44	2.48	0.17	59	267	55.0	1,580,039
1350N25	3.43	2.51	0.17	61	273	55.0	2,624,388
1350N22	3.45	2.43	0.17	61	281	60.6	2,839,057
1350N10	3.44	2.47	0.17	62	239	50.0	3,157,871
1350N7	3.39	2.44	0.17	62	210	45.0	5,109,252
1350N13	3.44	2.33	0.17	59	213	50.0	5,160,068
1350N18	3.38	2.42	0.18	64	207	45.0	6,337,954
1350N23	3.44	2.50	0.17	61	246	50.0	6,509,908

Table 3 – Fatigue test data of wires with transverse hole.

Specimen ID	D [mm]	d_h [mm]	$\Delta F/2$ [N]	$\Delta S/2$ [MPa]	N_f [cycles]
1350H3	3.38	0.70	495	75.00	87,242
1350H4	3.39	0.72	459	70.00	131,306
1350H7	3.38	0.73	423	65.00	590,395
1350H5	3.38	0.72	393	60.00	743,253
1350H13	3.39	0.72	393	60.00	796,499
1350H12	3.46	0.73	377	55.00	794,089
1350H2	3.41	0.77	357	55.00	831,325
1350H9	3.32	0.69	317	50.00	1,541,990
1350H11	3.38	0.73	325	50.00	1,892,158
1350H1	3.47	0.70	316	45.00	2,545,480
1350H10	3.38	0.75	290	45.00	5,014,845
1350H8	3.29	0.69	249	40.00	5,240,661



(c)

Figure 2 – Fatigue curves obtained for: (a) plain wire, (b) V-notched wire, and (c) wire with transverse hole.

FATIGUE ANALYSIS

A simple method to account for the stress gradient effect on fatigue life is to use an average stress instead of the stress at the hot spot. This approach can be traced back to the works of Neuber (1958) and Peterson (1959), who developed the so-called line and point methods. In the present work, the average stress is defined as

$$\sigma = \frac{1}{V} \int_V \hat{\sigma} \, dV \tag{1}$$

where V is the volume of the damage zone and $\hat{\sigma}$ is the stress tensor obtained from a linear elastic stress analysis. The shape of the damage zone is a semi-sphere of radius L, as shown in Fig. 3.

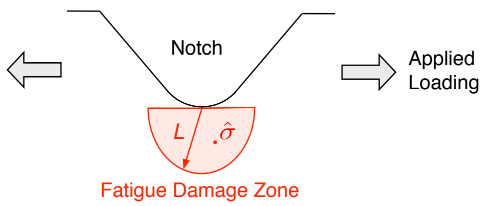


Figure 3 – Schematic of the fatigue damage zone in the vicinity of a notch.

To quantify the fatigue damage, the multiaxial version of the Smith, Watson and Topper (SWT) parameter based on the critical plane concept (Socie, 1987) is adopted. The reason for choosing the SWT parameter is because it usually performs better for aluminum alloys than other fatigue parameters (Dowling, Calhoun and Arcari, 2008). For a linear elastic stress-strain behavior, the SWT parameter can be written as

$$\mathrm{FP} = \frac{\Delta\sigma}{2}\sigma_{\mathrm{max}} \quad (2)$$

where $\Delta\sigma/2$ is the stress amplitude and σ_{max} the maximum stress in a loading cycle. The critical plane is defined as the material plane where the fatigue parameter expressed in Eq. (2) is maximum.

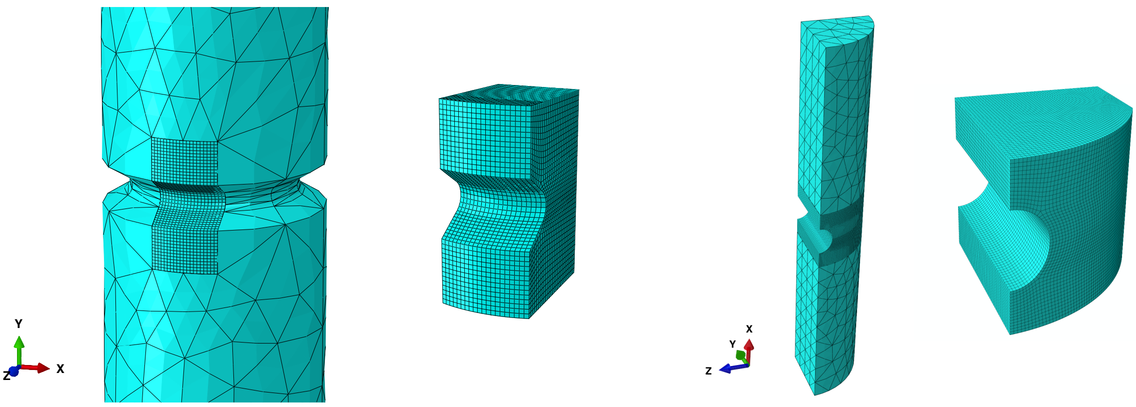
In the formulation developed by Neuber and Peterson, the size of the damage zone (also known as critical distance) was determined using an empirical expression. Later, Taylor (1999) proposed a procedure to obtain the size of the damage zone by using test data from specimens with high stress gradient (cracked or sharply notched specimens). However, Taylor's approach was limited to the prediction of the fatigue threshold condition of notched members. To extend this approach to the finite life region, Susmel and Taylor (2007) assumed that the size of the damage zone depends on the fatigue life according to a power-law relationship:

$$L = CN_f^d \quad (3)$$

where C and d are constants that can be determined using test data from specimens with a severe stress concentrator.

STRESS ANALYSIS

Linear-elastic stress analyses of the notched wires were carried out using the finite element software Abaqus. The finite element meshes for the V-notched wire and the wire with transverse hole are shown in Fig. 4. A partition containing a refined mesh was used to obtain better accuracy of the stress distribution near the notch root. For the V-notched wire the partition was created using eight node linear brick elements with reduced integration (C3D8R) and ten node quadratic tetrahedral elements (C3D10) were used for the rest of the wire. As for the wire with transverse hole, a 20-node quadratic brick element with reduced integration (C3D20R) was used in the partition and C3D10 was used for the rest of the wire. The FE model for the wire with transverse hole was designed using only a quarter of the geometry of the wire, in order to reduce the computation time.



(a) (b)

Figure 4 – FE meshes and details of the partitions for (a) the V-notched wire and (b) the wire with transverse hole.

The finite element simulations of the notched wires were used to identify the hot spot, defined in this work as the point of highest maximum principal stress. A python script was developed to compute the fatigue life using the hot spot as the center of the semi-spherical damage zone.

RESULTS

Correlation of the characteristic length versus fatigue life for the V-notched wires is shown in Fig. 5. Each data point was obtained by finding the characteristic length for which the estimated fatigue life matches the observed one. A power-law relation was then fitted to the data set by using the least squares method.

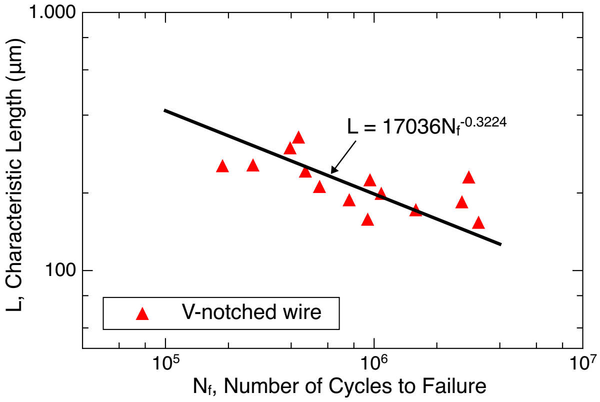


Figure 5 – Correlation between characteristic length and fatigue life for the V-notched wires.

Fatigue life predictions for the wires with transverse hole are compared with the observed lives in Fig. 6. All predictions were within factor-of-three boundaries and most of them were conservative. The scatter in the predicted lives is similiar to that of the calibration data.

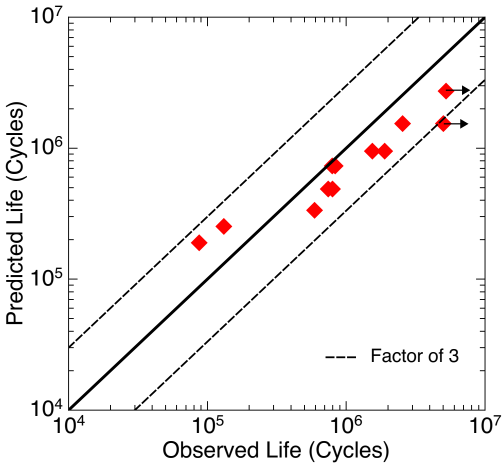


Figure 6 – Observed fatigue lives and predictions for the wires with transverse hole.

CONCLUSIONS

Wires made of 1350-H19 aluminum alloy taken from ACSR (Aluminum Conductor Steel Reinforced) overhead conductors were investigated in this work. Fatigue experiments were conducted on circumferentially V-notched wires with an opening angle of 60° and notch root radius of 0.17 mm, and on wires with a transverse hole with a diameter of 0.7 mm. The test data of the notched wires were within a factor-of-three scatter band in the observed lives. It was shown that a non-local version of the Smith-Watson-Topper fatigue model can be successfully calibrated using the V-notched wire test data. The fatigue life estimates of the wires with transverse hole were within factor-of-three boundaries. Fatigue life prediction of two contacting wires of an overhead conductor using the non-local version of the Smith-Watson-Topper parameter will be the focus of future work.

ACKNOWLEDGEMENT

The authors are greatful for the support provided by Empresa Amazonense de Transmissão de Energia S.A. (EATE). J. M. G Martínez is thanked for providing the plain wire test data. Fábio Castro acknowledges support from CNPq (contract 308126/2016-5). Ian Matos would also like to thank the support provided by CAPES.

REFERENCES

Dowling, N. E., Calhoun, C. A. and Arcari, A., 2009, “Mean Stress Effects in Stress-Life Fatigue and the Walker Equation”, Fatigue Fract Engng Mater Struct, Vol. 32, pp. 163-179.

Kaufman, J. G., 2000, ”Introduction to aluminum alloys and tempers.”, ASM International.

Neuber, H., 1958, “Theory of Notch Stresses”, Berlim: Springer.

Peterson RE., 1959, “Notch Sensitivity”, Metal Fatigue, pp. 293-306.

Socie, D., 1987, “Multiaxial Fatigue Damage Models”, J. Eng. Mater. Technol, Vol. 109, pp. 293-298.

Susmel, L and Taylor, D., 2007, “A Novel Formulation of the Theory of Critical Distances to Estimate Lifetime of Notched Components in the Medium-Cycle Fatigue Regime”, Fatigue Fract Engng Mater Struct, Vol. 30, pp. 567-581.

Taylor, D., 1999, “Geometrical Effects in Fatigue: a Unifying Theoretical Model”, International Journal of Fatigue, Vol. 21, pp. 413-420.

RESPONSIBILITY NOTICE